Safety and Integrity of Arctic Marine Pipelines

Draft Final Report

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C-CORE
Memorial University of Newfoundland
St. John's, NF, A1B 3X5, Canada
Tel. (709) 737-8354 Fax. (709) 737-4706

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Prepared By: Ryan Phillips & Radu Popescu Date: June 1998

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EXECUTIVE SUMMARY

The goal of the Pressure Ridge Ice Scour Experiment (PRISE) is to develop the capability to design pipelines and other seabed installations in regions gouged by ice, taking into account the soil deformations and stress changes which may be caused during a gouge event. Results from a continuing series of centrifuge model tests and finite element modelling are being used to adapt an existing soil/pipe interaction model for pipelines in gouge-affected soils. Pipeline design guidelines will be developed when the adapted model is complete.

The research funded by the MMS forms Phase 3d of the ongoing PRISE program being undertaken by C-CORE on behalf of oil companies, regulatory agencies and government bodies. The objective of this research is to confirm the magnitude and extent of sub-scour deformations in dilatant soil, through (1) direct field observations; (2) physical model simulations; (3) numerical model simulations; and, (4) development of an indigenous knowledge workshop. The results of this project will lead to more cost-effective designs and increased confidence in the operating integrity of buried offshore pipelines.

The field study conducted in Cobequid Bay, Nova Scotia provided limited data of sub-scour deformations under fresh ice scours in compact silt. The physical model ice scour simulations in dilatant soils under high-g were comparable with model tests conducted in earths gravity (1g). This consistency supports the use of centrifuge model tests to predict the soil response under full-scale ice scour events in dilatant soils. The numerical model simulations permitted large keel displacements in dilatant soil, adopting a Mohr-Coulomb soil model. The magnitudes and extent of the sub-scour deformations supported some of the observations from the centrifuge model tests. The analyses were strongly influenced by the soil's elasticity. Dr Robin McGrath assisted in the planning of a Traditional Knowledge of Sea Ice workshop at an MMS meeting in Anchorage on July 17th, 1997.

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1.0 INTRODUCTION

Pipelines on Arctic seafloors in the U.S.A., Russia and Canada are at risk to damage by the action of sea ice pressure ridge keels that gouge the seafloor. Sea ice forms during the long Arctic winters when the sea surface freezes. Storm winds during winter and early spring may put pressure on the 1-2m thick floating ice sheet, causing it to break and crush. This action creates linear mounds of piled-up ice blocks called pressure ridges; the keels of these pressure ridges may extend to 50m below sea level. Ice gouging occurs when the pressure ridge keel touches, penetrates and continues to move forward through seabed soils at velocities of several centimetres per second. The scouring action typically creates curvilinear troughs, called gouge marks, characterized by lateral mounds of soil created by the forward bulldozing action and lateral heaving induced by the scouring keel.

Oil and gas pipelines must be buried below the maximum expected gouge depth to avoid direct ice/pipeline interaction that would cause serious damage to the pipe. However, just as soil at the seabed surface is subject to large scour-induced displacements, the soil beneath a scouring keel also moves. These sub-scour deformations also must be taken into account as they may cause unacceptable shear and bending stresses in a buried pipeline.

Pipeline safety and integrity in areas affected by ice gouging must determine what constitutes a safe burial depth. The "safe" burial depth will not be the same for every region of the seafloor. This is dependent on three factors: (1) the maximum expected depth of ice gouging, which will determine the absolute minimum top-of-pipe depth of burial; (2) the soil type and condition which will affect the response of sub-scour soils to ice-induced stresses, and (3) the mechanism of load transfer from the deforming soil to the buried pipe. Thus the problem of pressure ridge ice gouging is, for each case, to determine a safe burial depth that not only avoids direct ice/pipeline interaction, but also minimises the risk of damage due to sub-scour soil movements.

2.0 BACKGROUND LEADING UP TO THE CURRENT RESEARCH

The Pressure Ridge Ice Scour Experiment (PRISE) is an ongoing jointly-funded, international, multiphase program. The goal is to develop the capability to design pipelines and other seabed installations in regions scoured by ice, taking into account the soil deformations and stress changes within the soil which may be caused during a scouring event. The need for this capability was identified during a round-table discussion with several oil companies and federal government representatives in 1990 during an international workshop on ice scour held in Calgary.

This innovative study, initiated and performed by C-CORE confirmed the possibility of deep-seated soil deformations beneath gouging ice keels. The study included a detailed and thorough analysis of deformation structures preserved in clay soil beneath ancient scour marks in the Winnipeg area of Manitoba. Mapping and measurement of the 10,000 year-old gouge marks, excavated by backhoe, proved conclusively that sub-gouge deformations in cohesive soils were both extensive (several metres below gouge base) and involved significant soil movements (up to 3.5 m along slip surfaces). The study provided the impetus for continued work to quantify the mechanisms and magnitudes of gouge-induced forces and soil movements. Since 1991 considerable progress has been made in this area, mostly through PRISE, which is led by C-CORE and joined by industry and regulatory agencies.

With respect to gouge-induced soil deformation, the seabed may be viewed as three progressively deeper zones, Palmer (1990). The top of Zone 1 is the seabed, and the base is the bottom of the expected gouge. As a gouging keel approaches a pipe buried in this zone, initially it will be lifted into the frontal mound of bulldozed soil. At first the pipeline will be pushed ahead of the ice keel but very soon axial tension will pull the pipe through the soil until it contacts the ice. At this point much of the ice force will be transferred directly to the pipe. For a large gouge, an ice force on the order of 200 MN may be expected (Woodworth-Lynas *et al.*, 1996). This is about 20 orders of magnitude larger than the pullover forces applied by dragging ship anchors that are known to damage pipelines severely. A pipe buried in this zone will be damaged.

Zone 2 is the soil layer immediately below the bottom of the ice gouge in which the soil deforms plastically but is never in direct contact with the ice. A pipeline buried in this zone will be dragged forward and perhaps pushed downwards by the moving soil, Palmer (1990). The pipeline section below the central region of the gouge will move with the soil, and will be relatively insensitive to such mass movements. However, below the margins of the gouge a pipe will be bent and stretched by relative movements between the dragged soil below the gouge and the non-moving soil outside the gouge, Nixon *et al.* (1996). Bending strains calculated for a conventional pipe below the gouge margin indicate that although it may be severely bent the pipe could withstand the large deformations without failing, Palmer *et al.* (1990). Thus some burial depth within Zone 2 may be acceptably "safe".

Zone 3, below Zone 2, is in the region where a pipe would experience loading from gouge-induced soil stresses, but the soil around the pipe would not move significantly. A pipeline in this zone generally will be safe. However trenching a pipeline into Zone 3, typically several scour depths below the seabed, is beyond the reach of conventional trenching equipment; although this Zone is desirably safe, it would likely be an uneconomic option.

Phases 1 & 2 of the PRISE project included phenomenological (field) studies, theoretical studies, and physical experiments, C-CORE (1993). Due to continuing industry interest, partly because of the potential offshore hydrocarbon developments around Sakhalin Island, Russia, Phase 3 of PRISE was initiated. This phase extended the database of physical experimentation and adapted an existing commercially available engineering model to the design of pipelines, C-CORE (1995a,b), Hynes (1996) and Lach (1997)).

Post-scour examination of the Phase 3a PRISE centrifuge model tests have shown that surface and sub-surface scour-induced deformation structures observed from the Phase 2 full-size scour marks in the field can be reliably modelled in the large C-CORE centrifuge. Sub-scour soil deformation empirical relationships for the ice/soil interaction at steady state were developed from examination of the physical centrifuge model test data. The observed extent and magnitude of sub-scour deformations for mean scour events were much larger than previously anticipated.

These PRISE tests provided data for scour depths and widths as large as 1.49 and 30m respectively in clay and 2.14 and 30 m in sand. However, extreme events on the order of a 5 m depth and/or a 100m width, might be expected in areas with development potential. Phase 3c of the program concentrated on determining the forces and soil deformation effects of *extreme* full-scale ice keel scour events in medium dense sand and stiff clay through the use of centrifuge modelling. These new data were used to expand the empirical relationships to include extreme scour events.

The Phase 3c tests have also indicated large and extensive normalised sub-scour deformations for extreme ice scour events. This test series has been extended to simulate both the ice scour conditions expected for the pipeline developments for Northstar, Alaska in silt and for Sakhalin Island, Russia in sand. The new tests conducted in a dilatant silt have also shown large and extensive normalised sub-scour deformations. These normalised deformations are apparently larger than those observed in compressible materials. It is this observation from centrifuge model tests that needs to be confirmed by further field evidence and numerical simulations.

A 3-day workshop was held in February 1998 on Ice Scour and Arctic Marine Pipelines during the 13th International Okhotsk Sea & Sea Ice Symposium, OSCORA (1998), in Mombetsu, Hokkaido, Japan. The workshop was organised by C-CORE, the Okhotsk Sea & Cold Ocean Research Association (OSCORA) and the Sakhalin Oil & Gas Institute (SOGI). The general aims of the workshop were to review progress in understanding the mechanics of ice keel scour, the ability to model the scouring process and the application of models to pipeline burial and protection. The workshop, C-CORE (1998c), attracted over 50 participants from Canada, Russia, USA, Japan & UK.

3.0 RESEARCH OBJECTIVES

The principal objective of the work being conducted for the MMS is to examine the magnitude and extent of sub-scour (Zone 2) deformations in a dilatant soil, such as compact silt. This information is essential to achieve the PRISE goal of designing pipelines and other seabed installations for regions gouged by ice, taking into account the soil deformations and stress changes which may be caused during a gouge event.

The objective was planned to be achieved through four tasks:

(1) Direct field observation of sub-scour deformations under fresh ice scours in compact silt in a tidal estuary;

(2) Simulation of these field ice scour events by centrifuge modelling;

(3) Development of the existing numerical model to predict sub-scour deformation profiles in dilatant materials, such as compact silt; and

(4) Assistance in developing the MMS Alaskan workshop on indigenous knowledge in technology.

This work was carried out as Phase 3d of PRISE under MMS contract 14-35-01-PO-14173. This 10 month project was awarded on 2 June 1997 and should have been completed by March 31, 1998. A project extension was requested until the end of June 1998 due to two delays. Task 2 was delayed due to a breakdown of the centrifuge from March through October 1997. This breakdown delayed the whole centrifuge testing schedule by 6 months, with a consequential delay to the tests for this project. Task 3 was delayed due to the departure of Dr Chan's postdoctoral fellow. Radu Popescu of C-CORE completed this task. Dr Popescu is a numerical analyst from Princeton University with experience in finite element modelling.

Tasks 1 to 3 are described in Sections 4 to 6 of this report. Task 4 was undertaken by Dr Robin McGrath and is described in Appendix A to this report.

4.0 FIELD STUDY

The field study was conducted in late spring 1997 during the ice break up in the Bay of Fundy, Nova Scotia to study sub-scour deformations under fresh ice scours in compact silt. The study is reported in detail by C-CORE (1997a) and summarised below. Vertical deformation tubes and markers were developed which could be placed in a tidal estuary at low tide. During the next tidal bore ice scours were created. A few of these scours intersected the tubes and markers. Excavation of these indicators permitted limited direct observation of subscour deformations.

Direct observations indicated that the ice in this area might not scour on each tidal cycle. It appeared that when the ice becomes embedded or rooted during an outgoing tide, it may remain so for some time. Pieces of ice were observed to simply "pop up" on a high tide which probably did not leave a scour. It appeared that if and when the ice broke free from its root, it might leave some ice embedded in the mudflats. For scours to occur on the mudflats probably requires the combination of a number of factors; ice conditions, tidal conditions, wind conditions, and wave conditions.

During excavation of the flexible marker tubes, a control tube, which was not scoured over, was also excavated. A difference could not be ascertained between the deformation of this and a tube over which a scour was known to have occurred. There may be limitations in using these vertical deformation tubes, as they may have been too stiff both vertically and laterally. A stack of copper tube segments was then tried as a marker. It is believed that, since the subscour deformation was shallow, it would have been more appropriate, and have increased resolution if a layered marker with less thickness than the copper tubes was used. This technique might have more potential than the flexible tubing if excavation tools and methods were refined.

The field program was impeded by three unexpected factors: an unforecasted blizzard which lasted for several days, a lack of suitable ice pieces and frozen seabed conditions. Despite these challenges, two types of markers demonstrated potential for measuring lateral subscour deformation and sufficient knowledge was gained to aid future field programs.

5.0 ICE SCOUR SIMULATIONS BY CENTRIFUGE MODELLING

It was originally proposed that the centrifuge modelling tests be conducted in a dilatant material, such as a compact silt, and the results compared to the field (1g) study. However, there were limited sub-scour deformation data obtained from the field study partly because the field tests were conducted in partially frozen ground. Other reasons are given in C-CORE (1997a). There were also technical difficulties in simulating the geotechnical properties of the field silt in the silts available to C-CORE in St John's.

The first centrifuge test was therefore designed to simulate two large 1-g ice scour model tests that had been conducted by C-CORE, Poorooshasb (1989), in medium dense sand. This medium dense sand, like compact silt, showed dilatant behaviour when sheared. The first test, designated PR3d-1, is reported by C-CORE (1998a). The results of the centrifuge test were comparable to the large-scale tests. The sub-scour displacement profiles were very similar, both attenuating at about one scour depth below scour. The scour forces from the centrifuge test were slightly higher than the full-scale test values, but the force ratios were quite similar. Differences were attributable to some differences in attack angles, sand type, scour width, and keel friction factor.

The second centrifuge test comprised two scour events conducted in a gravity consolidated dilatant sandy silt obtained from a tailings pond at Capital Products quarry outside St John's. The 2 events were undertaken in the centrifuge at 10g and 1g respectively. This second test, designated PR3d-2, is reported by C-CORE (1998b).

The sub-scour displacements under both events attenuated to zero around 6 to 10 scour depths under the scours. These values are comparable to a value of 7 scour depths reported by Poorooshasb and Clark (1990) from some large scale 1g low-strength silt tests. The lateral deformation magnitudes directly under the centrifuge scours were 0.8 to 1.2 scour depths. These ratios are consistent with values reported in large 1g sand tests by Paulin (1992) and previous centrifuge tests in sand reported by C-CORE (1997b). The vertical to horizontal scour force ratios were 1.3 and 1.5. These ratios are reasonable compared to average ratios of 2 and 1 measured in clays and sands respectively, C-CORE (1997b). The horizontal forces were normalised with respect to the scour geometry and the estimated undrained shear strength of the silt. These normalised horizontal forces were consistent with the data presented for other fine-grained soils by C-CORE (1997b).

The centrifuge model ice scour test results in dilatant soils obtained under high-g were consistent in terms of soil displacements and scour forces with comparable tests conducted in earths gravity (1g). This consistency therefore supports the use of centrifuge model tests to predict the soil response under full-scale ice scour events in dilatant soils.

6.0 NUMERICAL MODEL DEVELOPMENTS

6.1 Introduction

Considerable effort has gone into the development of a finite element method to verify and predict the results of centrifuge modelling of ice scour, seeYang *et al.* (1996), Lach (1997) and C-CORE (1995b). Two-dimensional analyses carried out in the plane of a section parallel to the gouge centreline have been relatively successful in compressible materials, such as soft clays, Lach (1997). Similar 2-D analyses in dilatant materials have met with limited success due to numerical instability that prevented approaching steady state scour conditions, C-CORE (1995b). Additionally, a 2-D approach does not allow clearing of the frontal surcharge, because it rapidly increases in size over short distances. This begins to have significant effects on sub-scour displacements that are not experienced in nature.

Task 3 of this project furthered the development of an existing numerical model to predict sub-scour deformation profiles in dilatant materials. Potential improvements considered included re-meshing; the addition of slip elements at the keel/soil interface; stabilization of the height of the surcharge, and adoption of an Arbitrary Lagrangian Eulerian approach.

This effort was led by Dr Andrew Chan of Birmingham University, England, who recently completed a review of the Phase 3b finite element modelling, C-CORE (1997b). Dr Chan was assisted initially by his postdoctoral fellow and then by Dr Radu Popescu of C-CORE. The workscope for this task was selected from Dr Chan's list of recommendations given in section 2.6 of C-CORE (1997b) as:

a) (Task 1c) Investigation of frontal berm material removal in conjunction with the two dimensional plane strain mesh

b) (Task 2b) Friction angle should be varied to consider the effect of shear capacity to the magnitude of lateral displacement and depth of influence

c) (Task 2c) Non-associative Mohr Coulomb model should be used for sand modelling. If possible, deviatoric hardening should be used for the dilatancy angle so that reasonable amount of dilatancy can be introduced while the soil will return to zero dilatancy when failing in constant volume shear mode.

Task (a) was not undertaken, see below. Tasks (b) and (c) are described in sections 6.3 and 6.2.

6.2 Mohr Coloumb Soil Models

Two material models: Linear Elastic and Non-associative Mohr Coulomb were implemented into the ABAQUS package via the UMAT material model interface. The linear elastic model was included to ease the testing and debugging of the material interface implementation. Both models were used successfully in the single point Soil model tester SM2D (Chan 1995a) and dynamic soil and pore fluid interaction finite element program DIANA-SWANDYNE II (Chan 1995b).

The Mohr Coulomb model (MOHR4) was also successfully implemented into another finite element package LUSAS via their material model interface with vigorous checking (GIBB 1995a, 1995b) and is being used for design in nuclear submarine dockyard facilities. The model is essentially similar to that described by Vermeer and de Borst (1984) and incorporated the conventional Mohr-Coulomb yield criterion with isotropic strain hardening for both cohesion and friction angle. A non-associated plastic flow rule enables contractive and dilatant behaviour during increments of shear stress to be modelled.

A backward Euler stress return algorithm is used to return a stress point to the yield surface when the yield stress is exceeded. The algorithm implemented is essentially similar to that described by Feenstra and de Borst (1989). Relative large departure from the yield surface can be handled efficienctly using this algorithm. The 'tangent cutting plane' algorithm described by Ortiz and Simo (1986) is adopted to recursively improve the stress estimate until the yield criterion is satisfied to within a specified tolerance.

Furthermore, the Mohr-Coulomb yield surface comprises 6 separate surfaces that intersect at corners for triaxial compression and extension. The stress gradient in both the yield surface and plastic potential are thus indeterminate at these corners. Special procedures are therefore necessary for forming the elastoplastic stress-strain matrix and during the stress recovery calculation where the stress gradients are required. A procedure described by Owen and Hinton (1980) and an algorithm presented by Punkaj and Bicanic (1989) are implemented to overcome this difficulty.

The interface between ABAQUS and the material model interface subroutine UMAT was tested using a case of 'finite strain consolidation of a two-dimensional solid' using linear elastic material model. The detail of this case is presented in ABAQUS v5.6 manual section 6.2.2. Identical answers were obtained using the ABAQUS linear elastic model and the linear elastic model implemented.

The testing of the Mohr Coulomb model (MOHR4) follows the procedure used in (GIBB 1995b) and (FEA 1997) which included:

a. Elastic strain path
b. Tensile strain path
c. Compressive strain path
d. Pure shear strain path
e. Pure shear strain path with non-zero dilation

All these single element tests obtained answers identical to the version implemented in other computer programs and analytical solutions.

Two meshes were created to model the ice-scouring process using the material model implemented. They were taken from C-CORE (1995b) and Lach (1997). Problems were encountered during the initial stress analysis stage and then in the early scouring stage. These problems could only be by-passed with large unrealistic cohesion values. Following subsequent investigations, the problems seemed to lie with the algorithm in handling tensile stress increments beyond the apex of the model, the iterative method used and the lack of a sub-stepping algorithm. Some of the problems were identified and could be readily solved using existing algorithms e.g. Chapter 14 (Crisfield 1997). However, this would involve major alterations of the material subroutine. Extensive testing would again be needed and it is not clear if these alterations will solve all the problems identified. Therefore an alternative work plan was adopted.

The 1998 version (v5.7_1) of ABAQUS incorporates a new simple non-associative Mohr Coulomb model with only isotropic hardening. This new version was mounted in the University of Birmingham on 13th Feb 1998 and later in the Faculty of Engineering & Applied Science at Memorial University of Newfoundland. Preliminary testing at Birmingham using the mesh taken from C-CORE (1995b) reveals that the analysis was successful and a scour distance of 4.55m was achieved. This ABAQUS version of the Mohr Coulomb model was adopted to progress the program. This model does not allow variation of friction and dilatancy angle with soil state. The studies therefore focussed on a range of friction angles (30° to 45°) and dilatancy angles, both of which were held constant during each analysis. The other factor considered was the effect of variation of soil modulii with confining stress.

From the theory manual of ABAQUS 5.7, Dr Chan noted that a rounding off profile has been used to remove the apex associated with the usual Mohr Coulomb model in the ABAQUS implementation. This is a further indication of why Dr Chan's Mohr Coulomb model was not successful.

6.3 Finite Element Analyses of Ice Scour in Sand

This section reports 23 ABAQUS fully-coupled analyses that were undertaken to study the effects of friction angle, dilatancy angle and elastic modulus. The effects of scour depth, soil cohesion, soil permeability and keel friction were also addressed. Dr Popescu undertook task (b), initially under the guidance of Dr Chan. The parameters for these runs are given in Tables 1 and 2 for scour depths of 1.485 and 0.5m respectively.

Table 1. ABAQUS Analyses - Scour Depth, D=1.485m

Run	Scour Length (m)	E-mod (MPa)(1)	Φ °	Ψ °	c' (kPa)	k (m/s)	Keel Frict.	Study *Remarks*
Test4	10.92	3.65 [C]	42°	42°	50	$2x10^{-11}$	0.1	*Extended mesh by 20m.*
Test5	0.07	30.0 [V]	35°	10°	5	$2x10^{-11}$	0.1	Variable E-mod. (cp Test45 and Test46)
Test6	0.05	45.0 [V]	35°	10°	5	$2x10^{-11}$	0.1	Larger E-mod cp Test5 Cohesion
Test7	0.14	45.0 [V]	35°	10°	50	$2x10^{-11}$	0.1	Cohesion x 10, cp Test6 Keel-soil friction
Test8	0.09	45.0 [V]	35°	10°	50	$2x10^{-11}$	0.01	Keel friction/10 cp test7
Test42	11.20	3.65 [C]	35°	10°	5	$2x10^{-11}$	0.1	Soil strength cp Test4 Constant E-mod.
T421	8.86	7.30 [C]	35°	10°	5	$2x10^{-11}$	0.1	E x 2 cp Test42
T423	6.70	11.0 [C]	35°	10°	5	$2x10^{-11}$	0.1	E x 3 cp Test42
T424	5.08	14.6 [C]	35°	10°	5	$2x10^{-11}$	0.1	E x 4 cp Test42
T422	0.53	18.3 [C]	35°	10°	5	$2x10^{-11}$	0.1	E x 5 cp Test42
Test41	0.54	36.5 [C]	35°	10°	5	$2x10^{-11}$	0.1	E x 10 cp Test42
Test43	11.10	0.37 [C]	35°	10°	5	$2x10^{-11}$	0.1	E / 10 cp Test42
Test44	14.20	3.65 [C]	35°	10°	5	$2x10^{-6}$	0.1	K cp Test42
Test45	0.19	10.0 [V]	35°	10°	5	$2x10^{-6}$	0.1	Scour depth cp D3 Variable E-mod cp Test5 and Test6 *Note different k*
Test46	1.07	2.00 [V]	35°	10°	5	$2x10^{-6}$	0.1	E / 5 cp Test45 and 44

(1) [C] – constant Young modulus [V] – variable Young modulus

(2) Φ - friction angle, Ψ - dilatancy angle, c' - soil cohesion, k - soil permeability

The meshes used for these analyses are shown in Figures 6.1 and 6.2 for the 2 different scour depths. These meshes were extended from those used previously by C-CORE (1995b). These extensions comprised the addition of 20m of elements in front of the scour, which is at the right hand side of the mesh. The continuum elements and interface elements were otherwise the same as those used by C-CORE (1995b). The mesh extension was necessary to accommodate the anticipated large keel displacements.

Table 2. ABAQUS Analyses - Scour Depth, D=0.50m

Run	Scour Length (m)	E-mod (MPa)(1)	Φ^{o}	Ψ^{o}	c' (kPa)	k (m/s)	Keel Frict.	Study *Remarks*
D1	17.50	3.65 [C]	35°	10°	5	$2x10^{-11}$	0.1	Scour depth cp Test42
D2	0.44	10.0 [V]	35°	10°	5	$2x10^{-11}$	0.1	Variable E-mod (contd).
D3	0.41	10.0 [V]	35°	10°	5	$2x10^{-6}$	0.1	k cp D2 Variable E-mod – cp Test45 (but D2 on have cut-off at a confining stress $p'=0.1p_{atm}$)
D4	0.65	2.00 [V]	35°	10°	5	$2x10^{-6}$	0.1	Variable E-mod: $E_o/5$ cp D3 and Test46 Dilation angle cp D51 & D6
D51	0.57	2.00 [V]	35°	0°	5	$2x10^{-6}$	0.1	- dil. angle = 0 (compare to d4)
D6	1.28	2.00 [V]	35°	5°	5	$2x10^{-6}$	0.1	- dil. angle = 5 (compare to d4) Study on friction angle
D61	0.61	2.00 [V]	30°	5°	5	$2x10^{-6}$	0.1	- friction angle = 30 (compare to d6)
D62	1.00	2.00 [V]	40°	5°	5	$2x10^{-6}$	0.1	- friction angle = 40 (compare to d6)

(1) [C] – constant Young modulus [V] – variable Young modulus
(2) Φ - friction angle, Ψ - dilatancy angle, c' - soil cohesion, k - soil permeability

The results of the analyses and the various studies are discussed below. The reader is referred to Tables 1 and 2 to identify particular analyses associated with the various parametric studies. Figures 6.3 to 6.6 demonstrate the results of the parametric studies on friction angle, dilatancy angle and cohesion respectively. The results show very little variation in the development of scour force with keel displacement, that is stiffness, to displacements of about 1m, Figures 6.3 to 6.4. There is a small increase in scour force with increasing friction angle, but effectively no change in scour force with dilatancy angle between 0 and 10°. (The model does not allow a dilation angle, ψ, less than zero which would simulate the contractive behaviour of loose sand). An increase in soil cohesion from 5 to 50kPa provided an increase in stiffness and scour force, Figure 6.5.

The increasing scour force, shown as the horizontal driving force, is less than 2MN/m of scour width after 11m displacement. This is equivalent to a normalized force of about 28, after C-CORE (1997b), which compares favorably with the measured normalized scour forces given in Figure 7 of that report. The calculated vertical to scour force ratio is up to 4.5 from Figure 6.6. This ratio is much larger than measured values of about unity, Figure 8 of C-CORE (1997b). In fact, in these analyses the calculated vertical to scour force ratio is never less than 2.65.

The calculated effects of friction angle, dilatancy angle and cohesion on stiffness and the development of scour force and force ratios suggest that these responses are controlled by sub-yield, that is elastic, soil behaviour. The studies with elastic modulus definitely confirmed this suggestion. Figure 6.7 shows significantly different stiffnesses for a range of different soil elastic modulii. The baseline case is for a Young's modulus, E of 3.65MPa. This value is much lower than those measured from triaxial compression tests on the PRISE F110 sand, Figures 3-18 and 3-20 in C-CORE (1995b). The use of a modulus of 10E however, which may be appropriate for loose sand, only permitted 0.5m of keel displacement before the analysis stopped.

The elastic modulus of soil is known to be a function of effective confining pressure. This also causes an increase in soil elastic modulus with depth. Analyses were run with the Young's modulus, E defined as

$$E_{min} < E = E_o \, (p' / p_{atm})^{0.5} < E_{max}$$

where E_o is the reference value, p' is the effective confining stress, p_{atm} is atmospheric pressure and the value of E is restrained by the limits E_{max} and E_{min}. The results, Figure 6.8, are comparable to the constant modulus analyses for comparable modulus values and keel displacements. However, the use of these variable modulii limited the keel displacements to a maximum of 1m. This limitation was attributed to the effect of low confining stress in areas, some with tensile stresses, behind the keel near the scour surface. The lower limit to E was successively increased to overcome this limitation with some success. An increase in E_{min} to 0.1 E_o allowed keel displacements of about 85% of the scour depth before the analysis stopped. The maximum confining effective stress was of the order of 400kPa, for example Figure 6.20, to give a maximum Young's modulus of only 2 E_o.

The main purpose of the finite element modelling was to confirm the magnitude and extent of sub-scour deformations in dilatant sand. Plots of some deformed meshes are given in Figures 6.9 to 6.11. The magnitude and vertical extent of sub-scour deformations in zone 2 below the keel are quite similar to those observed in the centrifuge model tests, Figures 10, 15 and 16 of C-CORE (1997b). The lateral and vertical deformations immediately under the scour are each about a scour depth in magnitude. The vertical extent of these deformations is affected by the surrounding soil's elasticity.

The large sub-scour deformations are accommodated by the elasticity of the surrounding soil, Figures 6.9 to 6.11. This effect is clearly demonstrated by comparison of Figures 6.9 and 6.10 from analyses with constant modulii of E and E/10 respectively. This accommodation is seen as vertical compression of the soil underlying the keel with lateral spreading to both sides and elastic rebound into the scour path behind the keel. This elastic accommodation also encouraged the mechanism of scour related deformation to be one of subduction. The transition to a ploughing mechanism was not apparent in these analyses.

Figures 6.9 and 6.10 show more surcharge in front of the scouring keel for the higher elastic modulus analysis. This surcharge height was much less than that observed in the centrifuge model. This surcharge was not considered to have a significant effect on the predicted scour forces. Task a, investigation of frontal berm material removal in conjunction with the two dimensional plane strain mesh, was not therefore considered necessary based on the results of these analyses.

The effect of soil permeability was also studied. The scour forces are compared in Figure 6.12 for Tests 42 and 44. There is no significant change in scour force. Chin et al (1993) suggest that:

$$v_p/k > 10^5$$

where v_p - penetration rate and k soil permeability (in same units) to achieve undrained cone penetrometer tests in sand. This ratio for these analyses is a minimum of about $5x10^5$ taking v_p as the scour rate. Undrained scouring might therefore be expected for this set of soil permeabilities and scour rate, although the drainage boundary conditions differ from a cone penetration event.

The excess pore pressure contours for these 2 analyses are also very similar, Figures 6.13 and 6.14. These figures indicate zones of positive pore pressure under the keel at depth and immediately ahead of the keel due to scour action and a zone of negative pore pressure immediately behind the keel. These zones correspond to zones of compression and shear dilation respectively. The excess pore pressures in the shear dilation zone are excessive, down to -570kPa. This is also reflected by the large effective confining stresses in this zone, Figure 6.20. This shows the need for a soil model, such as MOHR 4, in which dilation angle can be set as a function of soil state.

This section closes with a more detailed look at analysis Test44. The results shown from this analysis are typical. This analysis was continued to a keel displacement of about 29m. Results close to this displacement were significantly affected by the close proximity of the right mesh boundary. The results are normally shown at a displacement of 14.2m for comparison with previous analyses and to avoid this effect. The initial and intermediate (14.2m) positions of the keel are shown in Figure 6.15 together with selected nodes. The position of the keel face after 8m displacement is also shown.

The effective stress paths for elements associated with the selected nodes are shown in Figure 6.16. All the stress paths shown follow the yield surface, defined by the soil strength parameters, above stress levels of about 50kPa, until unloading occurs due to passage of the keel. The extent of the zone of plasticity under the keel can be seen from Figure 6.22, which presents contours of plastic shear strain with a maximum of 18%. This zone extends to a few scour depths below scour. The depth of this zone is a function of keel displacement. The extent of this contained zone is also a function of the surrounding soil's elasticity.

Soil displacements at the selected nodes within this zone are shown in Figures 6.17 and 6.18. The maximum lateral soil displacement, Figure 6.17, at node 3118 is 1.55m, that is greater than a scour depth. This displacement attenuates with depth as seen from nodes 9118 and 19118. The maximum lateral displacements at these nodes occurs at a keel displacement of about 9m, that is when the toe of the keel is immediately above the nodes, Figure 6.15. Similar observations can be made for the vertical displacements, Figure 6.18. After passage of the keel toe, the displacements decrease due to elastic unloading. This decrease is particularly significant in the vertical direction. These decreases would not have been so large had more reasonable, larger elastic modulii been used for the analyses. The effect of the right hand mesh boundary can be clearly seen after keel displacements of about 24m.

In summary, the existing finite element model of ice scour was developed, within available resources, to permit large keel displacements in dilatant soil. Keel displacements in excess of 10 scour depths were achieved. A Mohr-Coulomb soil model was adopted for a parametric study of soil strength parameters and dilatancy angle. The effect of elastic soil modulus was also undertaken.

Large sub-scour deformations and extensive zones of plastic straining were seen in these analyses. The magnitudes and extent of the sub-scour deformations supported some of the observations from the centrifuge model tests. The results of the analyses were however dominated by the effect of the surrounding soil's elasticity. This effect was seen in the development of scour force with keel displacement, vertical to scour force ratios and the sub-scour deformation field. The magnitude of the elastic soil modulii also controlled the amount of keel displacement in each analysis. Unrealistically low soil modulii were required to achieve large keel displacements.

The analyses supported the observed deformations from subductive behaviour during scouring. Analyses were not progressed related to the ploughing mechanism.

7.0 SUMMARY

The goal of the Pressure Ridge Ice Scour Experiment (PRISE) is to develop the capability to design pipelines and other seabed installations in regions gouged by ice, taking into account the soil deformations and stress changes which may be caused during a gouge event. This research forms Phase 3d of the ongoing PRISE program being undertaken by C-CORE. The objective of this research is to confirm the magnitude and extent of sub-scour deformations in dilatant soil, through (1) direct field observations; (2) physical model simulations; (3) numerical model simulations; and, (4) development of an indigenous knowledge workshop. The results of this project will lead to more cost-effective designs and increased confidence in the operating integrity of buried offshore pipelines. This work was carried out under MMS contract 14-35-01-PO-14173.

The field study was conducted in late spring 1997 during the ice break up in the Bay of Fundy, around Cobequid Bay, Nova Scotia to study sub-scour deformations under fresh ice scours in compact silt. The field program was impeded by unexpected environmental factors. Despite these challenges, two types of markers demonstrated potential for measuring lateral subscour deformation and sufficient knowledge was gained to aid future field programs. Limited data of sub-scour lateral deformations under fresh ice scours in compact silt were obtained.

The physical model ice scour simulation results in dilatant soils obtained under high-g were consistent in terms of soil displacements and scour forces with comparable tests conducted in earths gravity (1g). This consistency therefore supports the use of centrifuge model tests to predict the soil response under full -scale ice scour events in dilatant soils.

The numerical model simulations developed an existing finite element model of ice scour, within available resources, to permit large keel displacements in dilatant soil. Keel displacements in excess of 10 scour depths were achieved. A Mohr-Coulomb soil model was adopted for a parametric study of soil strength parameters and dilatancy angle. Large sub-scour deformations and extensive zones of plastic straining were seen in these analyses. The magnitudes and extent of the sub-scour deformations supported some of the observations from the centrifuge model tests. The analyses were strongly influenced by the soil's elasticity.

Dr Robin McGrath assisted in the planning a Traditional Knowledge of Sea Ice workshop at an MMS meeting in Anchorage on July 17th, 1997.

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Appendix A[1]

A Presentation on Traditional Knowledge of Sea Ice

Prepared for the Minerals Management Service, Anchorage

July 17th, 1997

By Robin McGrath, PhD

Many years ago, a former NHL hockey star moved to a small fishing village a few miles from where I live. The house he built, perched on the top of a steep incline overlooking the bay, was unlike any other in the community and when the roof was going on, the local fishermen tried to warn him that such a structure could never withstand the kind of winds experienced in that location. He chose to believe the expensive architect he had engaged rather than the poorly educated and rough looking men of Broad Cove. However weather is a great equalizer and although I was only about ten years old I still remember quite clearly the sense of satisfaction I experienced the day I turned the corner off the Thorburn Road and saw half of the famous man's roof lying in the next field. The retired athlete rebuilt the roof on his house several times before he bowed to an older, less-scientific wisdom and redesigned the roof to conform to local custom. This was my first conscious experience of the value of indigenous knowledge, and the price of ignoring it.

Traditional knowledge is defined as "the set of concepts, propositions, and theories unique to each particular culture group in the world," but in Newfoundland where I was born, it is simply called "mother sense", knowledge acquired through a combination of simple logic and the accumulated wisdom of those around you, usually the elders in your immediate family. Traditional knowledge and scientific knowledge are distinguished in part by how they are acquired: scientists tend to ask closed

1 This Appendix was not prepared or reviewed by C-CORE. The opinions and statements made herein are those of the author and may not represent those held by C-CORE.

questions that demand specific answers such as yes or no, while traditional knowledge disseminators tend to ask open-ended questions that allow for the unexpected. Scientific knowledge--which some would call beliefs--is absolute; traditional knowledge--generally called values--is relative. Scientific knowledge tends to be limited to a brief span of time such as a few years or decades, while traditional knowledge as expressed in myths and legends ranges back over thousands of years. Science is timeless rather than chronological, and traditional knowledge is situational rather than event-oriented. Science often does not take context into consideration, while oral tradition or knowledge cannot be interpreted out of context. Science focuses on the physical, while traditional knowledge is concerned with the historical, social, economic, and intellectual, as well as the physical.

One thing that traditional practitioners and western scientists have in common is their sense that the knowledge of the other is inaccessible due to language, and due to their belief in the sacred nature of the information. Both use languages that require a high degree of familiarity to be decoded, and both choose to disseminate their knowledge only in particular situations--the sweatlodge, the laboratory, the family circle, the fishing loft or the classroom. Unfortunately, when the traditional or indigenous person is the scientist, or the scientist is an indigenous person, you get a form of cultural schizophrenia, in which the person with both types of knowledge may apply both but is generally able to articulate only the one that he or she feels is acceptable to those around.

Scientists at Newfoundland's Centre for Cold Ocean Resources Engineering were doing ice impact studies in Labrador several years ago when the question of safety arose. There is no safe way to get on and off an iceberg. Almost all of the technicians had hair-raising stories of icebergs that flipped, fragmented and otherwise misbehaved while being subjected to the attention of various scientists. I sat in on one of these discussions and as it came to a close, one of the more experienced technicians said, half-jokingly, that he could tell when an iceberg was going to turn over because there were no birds on it. Another scientist later told me that an iceberg warns you when it is going to turn, by emitting a faint, high-pitched sound before it goes over.

Both of these ways of identifying stable and unstable icebergs are non-scientific. As far as I know, no-one has ever attempted to count the number of seagulls caught on fragmenting icebergs, nor have they ever tried to tape record icebergs as they disintegrate. This is traditional ecological knowledge, derived from generations of close association with icebergs. In Newfoundland, scientists used to learn these things from the fishermen who acted as boat handlers for them. In recent years we have trained our own scientists, born and raised in Newfoundland, but unfortunately they seem no better able to integrate traditional ecological knowledge than the scientists we used to hire from Britain or Upper Canada. C-CORE's ice-technician offered his seabird theory almost as a joke, not as a serious scientific observation that he learned from his father in Battle Harbour.

Each year the glaciers of Greenland produce about 40,000 icebergs and as many as 2,000 of these make their way down the East Coast of Newfoundland. In the past, these monsters--which can weight up to 10 million tons--have been a problem for fishermen, taking out stages and wharves and creating a hazard for schooners. Not only are icebergs harder than ordinary ice because they are produced under pressure, but they form spurs under the water that can rip the bottom out of a boat that gets too close, and when they move into shallow waters they tear up underwater cables, pipelines and fishing gear. Icebergs turn over as they melt, creating local tidal waves and smashing anything in their vicinity, and they can also explode from the compressed air trapped in them, tossing fragments of ice for hundreds of meters.

Fishermen in Newfoundland and Labrador learned to deal with icebergs out of a sense of self-preservation, using them as a source for fresh water for ships and, before the introduction of refrigeration, using berg ice as a way to preserve bait such as capelin and squid. Berg towing was a common practice for the preservation of nets, boats and stages, and if the iceberg couldn't be towed, the men would use sturdy, metal-tipped poles to push the icebergs away. Shrewd schooner captains learned to pass icebergs on the weather side, knowing they tend to move to windward, and according to Moses Bursey, a fisherman from Old Perlican who wrote about icebergs in 1912, fishermen were even known to throw a line on a fast-moving iceberg and hitch a ride. The vessel would be moored stern-on and "with a good strong cable, and every bit of canvas tied up, these icebergs would sometimes tow them at the rate of seven knots an hour, dead to windward." If the iceberg turned, the vessel could lose its jib-boom or bowsprit, or it might even founder.

In my own community, at about the same time the hockey player lost the roof of his house, the public wharf was destroyed by a giant iceberg which swept into the bay and smashed it to pieces. A prominent local fisherman had dreamed in the preceding week that this was going to happen, and the story was all over the community even before the iceberg was in sight. It may have been a coincidence, but this man knew the bay like the back of his hand and was very sensitive to local ice and weather conditions. It is quite possible that his dream was the result of an involved series of observations and calculations.

A complex terminology has developed in Newfoundland to describe ice and icebergs. There are clumpers, growlers, bergy bits and ballycadders, pummy, sish, slob, candle, gall and pinnacle ice. Ice blink is the white glare of low clouds over distant ice, and gleen is a halo produced by the reflection of light off the ice. Men involved in the seal fishery learned to locate large herds of seals by looking up into the sky and seeing the dark patches on the ice reflected in the clouds. In fact, Newfoundlanders have as many words for ice as Inuit have for snow, and a few of these terms, such as growler, have even been adopted by the scientific community. By rights, one should expect native Newfoundlanders and Inuit to dominate the world in the science of ice and snow, but this simply isn't the case.

When traditional knowledge and western science fail to combine in the one person, problems develop. Some time ago, one of C-CORE's scientists was with a crew doing testing on fast ice in the Great Northern Peninsula. He told me of how the crew was billeted with an elderly lady in the community who took a great interest in what they were doing. One morning, over breakfast, she commented that they would not be going out onto the ice that day. They assured her that they would, and she responded with some concern because, she insisted, the ice was going to break up. There was no sign of the ice breaking, nor did the technicians' scientific instruments suggest it would, so they went ahead with their work. The ice broke, they drifted seaward, and had to be rescued by local fishermen.

C-CORE's scientist, the one Newfoundlander on the crew, was very uncomfortable when he told me this story. He said that nobody in the community blamed the other scientists for going out on the ice, but everyone blamed him, including himself. He was in an impossible situation--when he was a student, he had not gone home in the summer to work on the boats with his father as many other students had; rather he ensured his successful career by working at the university and increasing his skills in western-style science. On this occasion, he didn't know when the ice was going to break, and he didn't even know enough to realize that a woman who had watched the ice break up from her kitchen window every spring for 76 years was probably the most sensitive instrument he could have consulted to find out. The same, of course, would be true for a native scientist born in Baffin but educated in Ottawa, and it will continue to be true unless we can find some way of integrating traditional ecological knowledge into mainstream science.

At C-CORE, an enormous amount of attention is given to ice and icebergs. It is estimated that on average, 11 icebergs a year will collide with a platform situated in Newfoundland's Hibernia oil field and since icebergs can range in size from one hundred tons to ten million tons, an encounter between the two is a serious threat to both lives and the environment. Their ice-impact studies address this problem. At C-CORE's centrifuge, which is one of the best in the world, scientists are also building tiny models to test the scour effect of icebergs on buried pipelines. Scours have been seen in water 230 meters deep, and their effect as measured on fossilized scours in the Winnipeg area suggest that a scour two meters deep can produce faulting and cracking down a further five and a half meters. The implications of these figures for pipeline construction in the north is obvious. What is not obvious is how traditional knowledge, either that of Inuit or of Newfoundlanders, can help solve these problems, or even solve some of the problems scientists doing research encounter as they try examining how ice behaves.

In any type of Inuit literature--the history of the material culture, legends, memoirs, or myths--you find recurring references to icebergs and ice that tell us a great deal about these phenomena, as well as a great deal about Inuit themselves. Traditional Inuit were nomadic; they had limited material out of which to create things, and could carry little with them, so the land itself, not just the product of the land, became one of the objects they used for the sustenance of human life. A rock, picked up and laid on top of another, becomes an inukshuk, marking fishing lakes and sled trails. Clouds in the sky, under the right conditions, become what is known as a water map or sky map, reflecting large land masses or even huge caribou herds. A pan of ice, moved with a pole, becomes a barge to ferry a duck or seal hunter out to collect his catch.

In the Avataq Cultural Institute's report of the Traditional Medicine Project, ice is listed as a healing agent for treatment of fever and other problems. In books on material culture, ice appears as a building material, providing windows for igloos, shelters for fishing and so on. Levi Iqalujjuaq, in his autobiography *The Life of a Baffin Island Hunter*, devotes a full chapter to ice and icebergs. Many of his observations are of a very practical nature, such as the suggestion that if you are on sea ice that is breaking up you should head for the highest iceberg in the area as it is probably grounded and unlikely to float further from shore. He also deals with the psychological, and suggests that in such circumstances it is "best that you be afraid for a time" as this will prompt you "to make a sensible decision as to the next move." Iqalujjuaq even warns of the hypnotic effect of staring down a seal hole--in at least one case a man simply allowed himself to be pulled into the water and drowned.

If you move away from factual literature and look at myths and stories, you get a broader picture of the place of ice in Inuit society. One of the oldest stories about ice tells how the Inuit epic hero, Kiviok, encountered a cannibalistic sorceress who wanted to seduce and then eat him. When he attempted to escape in his kayak, she cut her genitals off and flung them after him, thus creating clams, and when that did not stop him she hurled her ulu, her woman's knife, after him. The knife skipped across the water like a stone, and wherever it touched the water formed a skin of ice. That is why water now freezes over in winter. Ice is associated here with the feminine, with danger, and with sexuality.

The story of how Marble Island in Hudson's Bay was created also associates ice with women. It tells of a hunter called Uanik who was forced to move with his family to a new area because of a scarcity of game. One old woman, who was too weak to travel, insisted upon being left behind. One day, while looking out to sea, she spotted an iceberg which looked like an island and wished that she could live there forever. The iceberg was transformed into an island of granite and today, visitors still go up the beach of Marble Island on their hands and knees as a sign of respect for the spirit of that old lady which is still thought to inhabit the place.

The Cape Dorset historian, Peter Pitseolak, also associates ice with women and procreation. In his pre-natal memoirs, he recalls sliding down between two clapping mountains of white ice; the icy cliffs are his mother's thighs and he is being born.

Each of these stories embodies attitudes towards ice that are evident throughout Inuit literature. In the story of Kiviok and the sorceress we have a description of ice that is scientifically accurate. Sea ice is less brittle than freshwater ice. It is flexible, it can ripple and sag and respond to tides without breaking, and it is far more like skin than like glass. In the Marble Island story, there is no great distinction made between ice and land, and this attitude is reflected in the *Inuit Land Use and Occupancy Report*, where traditional trails and camps are marked on water as well as on land. Ice, like land, is habitable and can sustain life, and so must be treated as if it were land and, as a result, occupancy of the sea ice and the right to travel over it is included in all Inuit land claims agreements. In the story of the clapping mountains, a variation of which can also be found in the Kiviok cycle, ice is directly associated with birth and regeneration, with renewal rather than destruction. Ice is not just inert, frozen water--it has the power to heal, nurture, hypnotize, kill, feed or accommodate us. It should be thought of as a living entity.

Some time ago I heard a report on the radio about a scientist from Memorial University's Institute for Marine Dynamics who had traveled to the north pole as part of a research team. Media reported the extraordinary news that the team had found algae growing on the sides of icebergs, beneath the water, and that a large iceberg is an ecosystem of its own. This may have been news to the CBC, but I doubt that it was news to the scientist, or to most Inuit or even to Newfoundlanders of my father's generation. We know that hydrothermal vents in the ocean floor create ecosystems because of the bacteria and the heat being released, but icebergs create ecosystems too. Icebergs begin life as moving objects but they often ground for long periods of time and then tend to act more like islands than like ships. They are famous for attracting polar bears, which hunt seals from them just as humans do, and since the seals congregate where there is food,it makes sense that icebergs in some way add to the food chain. Proving the part the iceberg plays in the food chain is another thing, of course, and I expect that is what the IMD scientist had been doing.

Accepting icebergs as ecosystems might have happened a hundred years sooner if we had listened to native people, but too often information embedded in a narrative context is assumed to be fiction. The western concept of fiction, however, is unknown in the aboriginal world. Myths and legends, even when they appear to contradict the evidence of the senses, were considered to be true, however confusing and mysterious. Ice worms, for example, are known throughout the north and I have often seen drawings and carvings depicting them, yet it took me some time to realize that they were not just fictional, but were real.

Back in the early 1970s, when I first saw ivory carvings of ice-worms being produced in a Netsilingmiut community in the Central Arctic, I asked about the existence of such creatures. Inuit always assured me that they did exist, and non-Inuit assured me that they did not. It was some years later that I learned that there are, in fact, three worm-like insects and an algae commonly referred to as ice-worms because of their tolerance of freezing and overwintering in exposed conditions such as those on glaciers and ice floes.

The ice-worm is a benign and somewhat humerous subject for carvers and storytellers alike. In the Western Arctic, there is an Inuit myth about a Sikusi, "a woolly and mischievous ice-worm and a notorious melter of ice," and this humorous aspect of ice-worm lore has been transferred into non-native folklore in the north. Probably the most famous example is found in Robert Service's "Ballad of the Ice-Worm Cocktail," where he describes a trick played upon a pretentious Englishman, one Major Percy Brown. Brown is challenged by some old sourdoughs to prove his mettle at the Malamute Saloon, so Barman Bill sets to work and in a short time produces an ice-worm cocktail:

His silver cups, like sickle moons, went waving to and fro
And four celestial cocktails soon were shining in a row
And in the starry depths of each artistically piled
A fat an juicy ice-worm raised its mottled mug and smiled.

Brown manages to choke the drink down, but it comes back up even faster, proving that he's not a real sourdough after all.

And ere next night his story was the talk of Dawson Town
But gone and reft of glory was the wrathful Major Brown;
For that ice-worm (so they told him) of such formidable size
Was a stick of stained spaghetti with two red ink spots for eyes.

The ice-worm also make a comic appearance in an even better known popular ballad that dates back to the turn of the century. "When the Ice-Worms Nest Again" was thought to have been composed on the Yukon River and brought across the mountains during the oil stampede at Fort Norman. The subject of the song is romance under the midnight sun, and the chorus goes as follows:

In the land of the pale blue snow
Where it's ninety nine below
And polar bears are roaming o'er the plain,
In the shadow of the pole
I will clasp her to my soul--
We'll be happy when the ice-worms nest again.

The somewhat comic and frivolous nature of the carvings and stories about Sikusi were seen by the non-believers as proof that ice-worms were a product of the supposedly primitive native imagination. Real science is serious, so anything funny must be dismissed as an illusion or a lie.

The fact that many of the native Newfoundland, Indian and Inuit legends about ice have been found to contain important scientific information does not mean that scientists are any less skeptical today. The ability of the ice worm to melt igloos and thaw large bodies of ice has never been seriously investigated, nor is it likely to be unless our attitudes change. Two years ago, I spoke to ice-scientists who were working in Labrador and they told me that they found information from local informants to be of no value, citing as an example a belief common to Labrador that ice rots in spring and sinks. When I suggested that perhaps the ice appears to sink because it is frozen to the shore and the water rises, a phenomenon I have seen in Baffin Island and the Western Arctic near the mouths of large rivers, they rolled their eyes at me as if I was as crazy as those people from Packs Harbour. A suggestion from fishermen that sea water is denser in Autumn received similar treatment.

Accepting that ice should be treated as if it were a sentient being, or at least as an entity like a ship or an island, will not solve all the problems of how to extract traditional knowledge about ice from the plethora of stories native people and Newfoundlanders have to tell about it, although it is a good beginning. One of the many things tradition tells us is that ice has a voice, not just a metaphorical one but a literal one. Hunting memoirs are full of warnings that silence is necessary when one is out on the ice, that freshwater ice makes more noise when it breaks than saltwater ice does, that you have to listen to the ice all the time. One of the best known Inuit poems, by the Igloolik hunter Ivaluarjuk, describes how, in despair, the poet lies down on the ice in winter, ready to die, but then he imagines he hears the buzzing of mosquitoes and recalls an enormous bull caribou he speared in the summer, which gives him the courage to struggle on. The ice speaks to him. When the Inuit poet Aijut imagines his own death, with his corpse blocked into a snow-hut, it is the loud cracking of freshwater ice echoing back from the sky that gives him the horrors. The ice speaks not just to the imagination, but directly, literally into the ear.

Scientists, too, are beginning to realize that they have to listen to the ice. Julie Cruikshank, while researching glacier movement in the Yukon, discovered that among the Dene there is a prohibition against frying food near glaciers because the glaciers are thought to be inhabited by giant snakes. These snakes bear a striking resemblance to the comic ice-worm Sikusi--if they smell grease, they emerge, causing glacial surges and radiating intense heat that melts the glacier, flooding the land. Such a prohibition, from a scientific point of view, must seem absurd, but taken in the context of native attitudes towards ice, it is not.

Comments made by a C-CORE ice-scientist for a popular newspaper article help to make sense of this taboo. Dr. Deborah Diamand spent a lot of time on icebergs, and on several occasions had to be pulled from the water when they turned over on her. Diamand reports that one day she was on an iceberg conducting studies when a large piece of ice broke off and fell into the water. She says "The pieces in the water were popping, sputtering and crackling quite loudly. it sounded like something frying." This crackling and spitting noise is caused by air escaping from the ice as it fragments.

If you are an aboriginal living on a glacier, the sizzle and pop of your favourite fish recipe is likely to mask the sizzle and pop of an imminent ice-surge and flood. If you are camping on or near a glacier or iceberg, you don't want people frying chips there. *The Jerusalem Post* recently reported a request by the municipality of Jerusalem that the air-force refrain from producing sonic booms while overflying the city because of the panic it caused ordinary citizens--City Hall and police headquarters receive literally hundreds of calls from distressed citizens every time it happens. The head of Jerusalem's security department wrote that in light of "the high sensitivity among the residents of the city to the sound of any kind of explosion" those responsible should show some restraint. The analogy is obvious. If you live in a war zone, you won't want people setting off firecrackers in the street, and if you live on an iceberg or glacier, you won't want them frying food.

As a Newfoundlander, I should know quite a lot about ice. I have been observing ice and icebergs all my life, and my father and my older brother went to The Front back in the days of the seal fishery. I have traveled over hundreds of miles of sea ice, by foot and by skidoo, and thousands of miles of ice by helicopter and small fixed-wing aircraft. I know the difference between a bergy bit and a growler, and between slob ice and candle ice. However, I can't describe or document how I know what I know. When, in the famous Newfoundland folk song, the woodcutter from Tickle Cove Pond who lost his horse through the ice sings "The very next minute the pond gave a sigh/And up to our necks went poor Kitty and I," I know what that sigh sounds like. I've been soaking wet and up to my neck in slob ice on more occasions than I care to recall.

The question we are left with is how do we obtain traditional knowledge about our environment if training Newfoundlanders and Inuit to become scientists apparently wipes out their ability to trust what they know to be true? If we were to go out and ask all the old men and old women in Newfoundland where the codfish have gone, we'd probably be no closer to an answer than we are now. If we educate our children to be scientists just the way they are educated in Montreal or Paris or Hong Kong, we'll be no closer either. But if we educate our children to know and appreciate traditional culture, the songs and the stories, the history and the practices, we may find aspects of our society that have been invisible to us, new ways of managing our fishery that will work better than the ones that landed us in this crisis. We may find that we can hear the voice of the ice, and the voice of the rock, and the voices of all our ancestors and descendants.

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Some Problems and Some Possible Solutions Concerning Traditional Knowledge Discussed at the July 17, 1997 Meeting at Minerals Management Services

How can scientists overcome the time constraints or a field season or granting program without excluding traditional knowledge?

The difficulty of extracting traditional knowledge within the time frame usually required by environmental impact studies is not an easy one. Western science and traditional knowledge work within different time frames, and western scientists have difficulty accepting the need to move slowly when collecting traditional information. Sometimes it is possible to shorten this process by doing adequate background research--i.e. familiarizing oneself with the cultural context, the myths and legends, the basic structures of the language or dialect being used, the genealogy of the informants etc. Sometimes, however, only time will release the information that is needed. It was generally agreed that public inquiries are an inappropriate and unreliable forum for collecting traditional information.

Who should be chosen as informants?

The community will probably do the choosing, though this may not always be obvious. Consensus rather than individual testimony is generally the acceptable source of traditional knowledge; however, everyone who wishes to contribute must be heard. One well known Canadian linguist was heard to complain that sometimes people who had never said a sensible word in their entire lives were suddenly transformed into "elders' when they reached the magical age of 65, and expressed a desire for a categorization of older informants into "elders" and "geezers". While his frustration was understandable, it is important for scientists to realize that respect for elders is paramount in native and some non-native communities, in part because traditional knowledge is not dependent upon the logical or intellectual abilities of the individual. Traditional knowledge is frequently acquired passively, simply through repetition or the passage of time. Therefore, even self-promoting, tiresome or apparently thoughtless individuals can be sources of important information and must be given due respect. Again, this is one reason why group discussion or cumulative collection (not public forum) is a preferred method of extracting traditional knowledge.

Are computers any help?

There has been a trend recently towards using computer programs to extract indigenous knowledge from native elders. I don't think it will work, but for those with greater faith than me, I suggest you pursue the Macintosh KSSO program being used at the University of Calgary on behalf of the Dene Cultural Institute. Try contacting the Dene Cultural Institute, General Delivery, Fort Resolution, NWT, Canada X0E 0Y0 Tel 403-394-3219. Pete King, Alexis Arrowmaker, Nick Black, George Blondin and Leo Norwegion were the Dene elders advising the Traditional Knowledge Working Group.

There has been some success using Geographic Information Systems in relation to Innu Land Claims in Labrador and aqua culture on the island of Newfoundland--Al Simms at the Dept. of Geography, Memorial University of Newfoundland may be able to tell you more, but any GIS expert can help define the boundaries of the programs.

What other strategies might work?

1) Work with informants as partners, not as subordinates. If you use their material, make sure their names go on the papers. Educate informants and allow them to educate you. See the works of Ann Gunne, a biologist with the Northwest Territories Government, as a model of how to do this.

2) Go back into the literature of the cultural group you are working with. Look at legends, material culture, poetry, drama, games, etc. for all references to the subject you are interested in. Each individual reference may seem useless but collectively they may show a trend and at the very least these references will help you decide what questions to start with.

3) Go back into the literature of early anthropologists and scientists and extract traditional knowledge from between the lines of their scientific papers. Try to get t their field notes. In most cases, it is obvious when they are getting their information from native or local informants, even if it was not then acceptable for them to admit this outright. Again, it may not give you answers but it will give you useful questions.

4) Consult a folklorist, or a linguist if you can't find a folklorist, before beginning interviews. In many cases, the shortest distance between two points is not a straight line. In order to avoid getting the answers the informants think you want, it may be necessary to take a more roundabout route, particularly if the inquiry involves religious or otherwise sensitive material. If you are interested in flooding trends, you may find it more helpful to ask about campsites; if you are tracking transmission of disease, you may need to focus upon family trees first. Closed questions are often the product of closed minds. Broaden your field of interest so you are less likely to miss the target.

5) Be very careful with language, and remember that English as spoken in isolated areas may often be as foreign to western scientists as a native language. As is evident from the attached sample listing of Newfoundland and Inuit sea-ice terms, there is a lot of scope in linguistic inquiry, and a lot of room for error. The Inuit word annarltoKaK may translate as dirty ice (ice that is black from volcanic dust or accumulated soil), but in Newfoundland, the English word dirty means dangerous or unpredictable when applied to ice. Native languages and English dialects are a rich source of traditional information but many scientists have little patience with the process of collecting that information. If this is the case, find someone who has an interest and some background in linguistics or etymology.

6) Be more creative about what kind of traditional knowledge you are collecting and what can be useful to scientists. Henry Lickers, the Akwesasne zoologist, addressed this same problem several years ago when he spoke at a Social Sciences and the Environment Conference in Ottawa. Lickers described how he went away to university, did his degrees, and then came back and said to his grandfather, "Okay grandfather, tell me everything you know about the animals." As he quickly discovered, it's not that easy. Ten years later, after getting involved with negotiations to come up with a joint management system for the Model Forest that was being developed in conjunction with Abitibi Price, Lickers realized that the real contribution he had to make was political. Traditional Mohawk government, which works by consensus and has built-in protection for weaker partners, is one of the most sophisticated and successful forms of political governance there is. It may not tell you what animals eat what foliage but it is invaluable traditional knowledge that has helped make the program a success.

How can western scientists prevent western education from dominating traditional science in students from traditional communities?

They probably can't, but they can minimize the damage and loss to people from traditional communities, particularly the young, by paying more than lip-service respect to the traditional culture, by taking an interest and contributing locally specific material to the curriculum development programs in the schools, by acknowledging the part played by elders, informants and assistants in retrospect as well as in future endeavors, by hiring local people as assistants even if it means not hiring their own undergraduate students, by encouraging and assisting local informants to further their education, by paying professional translators rather than using whoever happens to be around.

Are there other traditional knowledge groups who might help?

Yes, dozens, if not hundreds of them. Try the University of Alberta Indigenous Knowledge

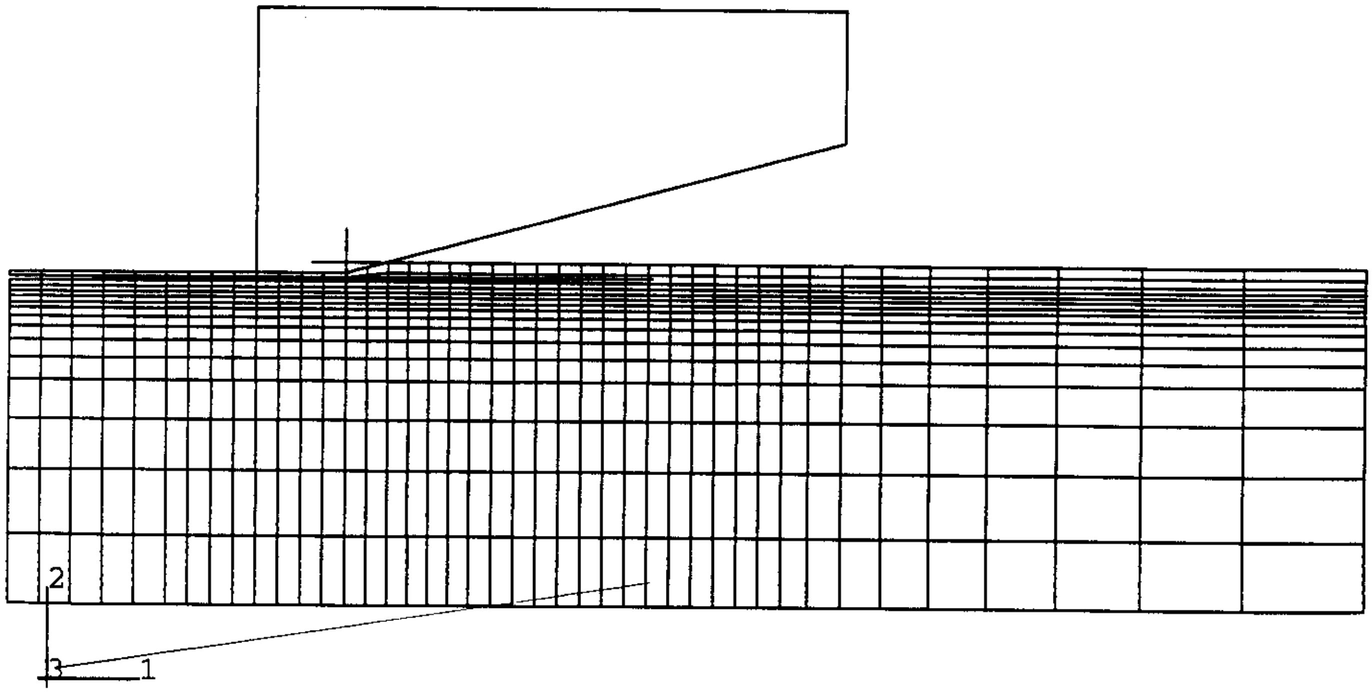
Network, Canadian Circumpolar Institute at the University of Alberta, Old St. Stephen's College, (8820-112St.), Edmonton, Alberta, Canada T6G 2E2. They can probably put you on to similar groups.

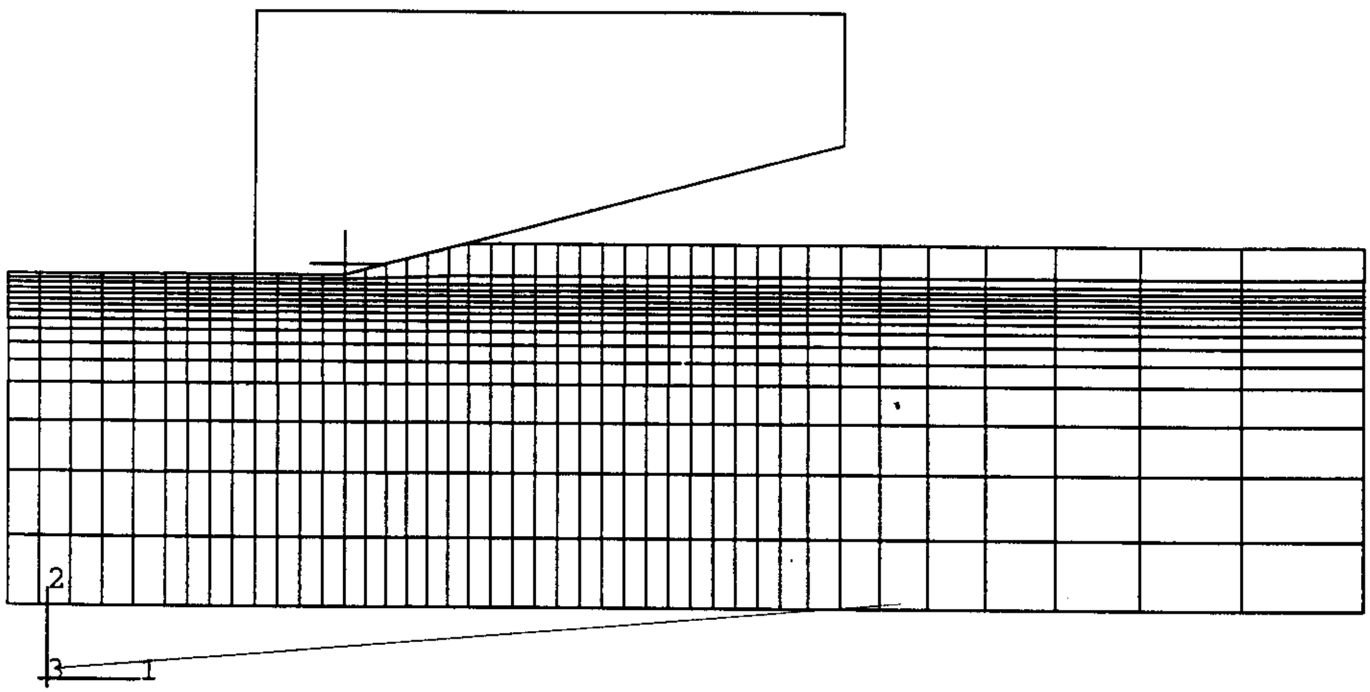
Traditional Sea-Ice Terminology

Newfoundland	*Labrador Inuit*
slob (heavy, slushy, densely packed mass of ice)	siKKu (ice)
ballycadder (frozen to the shorline)	Kachvak (drift ice)
ice gall (ice through which water oozes up)	annarlotoKaK (dirty, black drift ice)
growler (ice the size of a dory)	kakivok (young ice broken by wind)
lolly (soft ice forming in water	allortortauvok (ice drifted on the shore)
dirty ice (dangerous, unpredictable)	kaimgok (fresh ice on sea margin)
growler (ice from disintegrated berg)	tok (thick ice)
clumper (small floating pan or berg)	perKallujaK (iceberg)
pummy (smashed or ground ice)	nillaK (clear ice)
sish (granulated ice floating on surface)	massaleraK (new salt water ice)

Also in Newfoundland: anchor ice, bergy bit, grower, brash ice, berg, candle ice,ice-loom or ice glim, pan, ice rind, ice quar, and dozens of other terms used alone and in combination. (Compiled by Robin McGrath from works by Geo. Story and W. Peacock)

Dirty Ice: Slob mixed with snow--i.e. dangerous or hazardous.
Lolly: Soft ice forming in water when it first begins to freeze.
Cocky pan:
Pinnacle
Piqalijuaq: ice berg

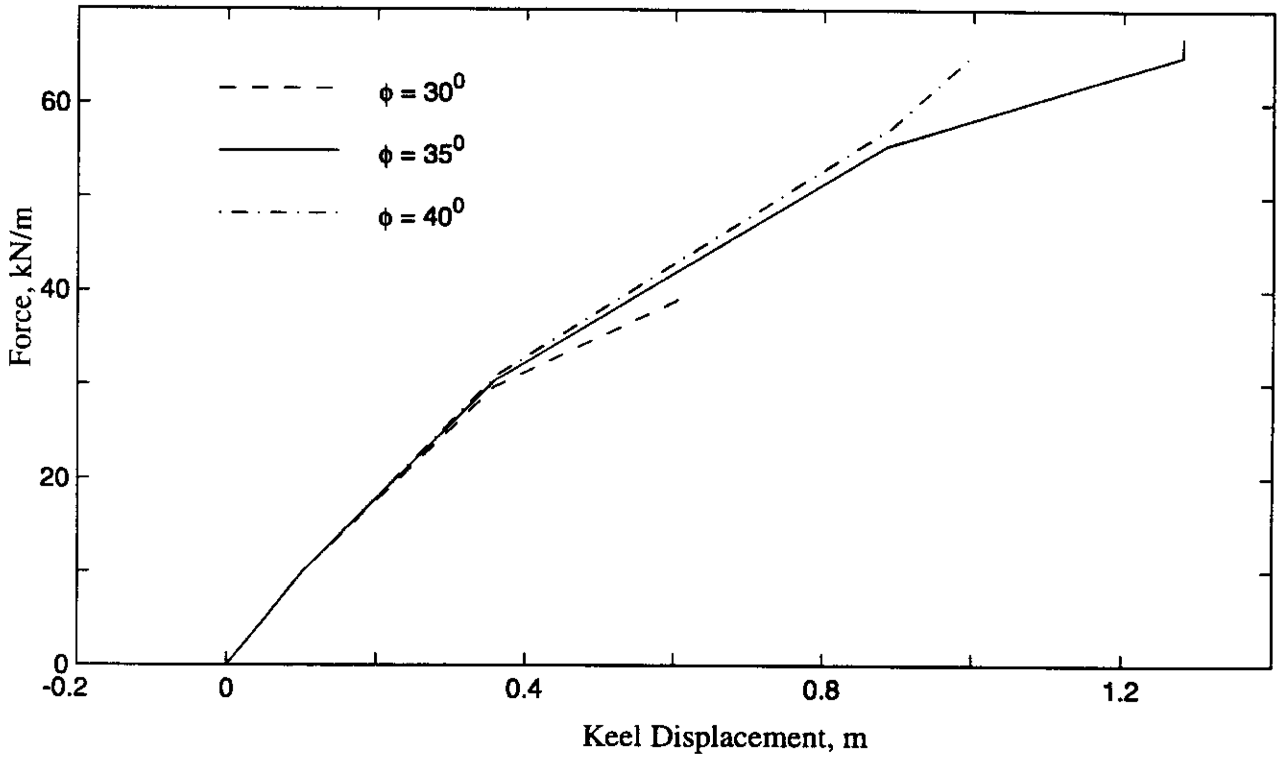


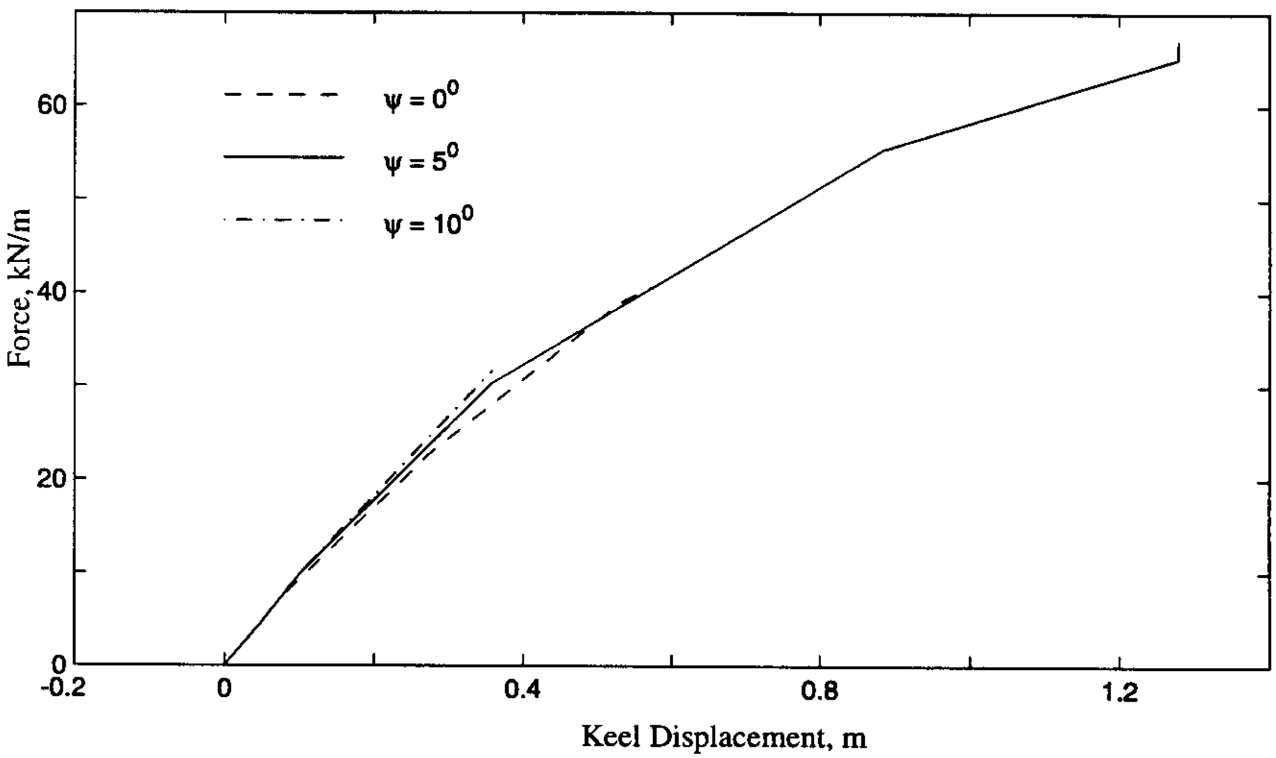


C-CORE

Finite Element Meshs for Scour Depths
0.5m and 1.485m

Fig. No.
6.1
6.2

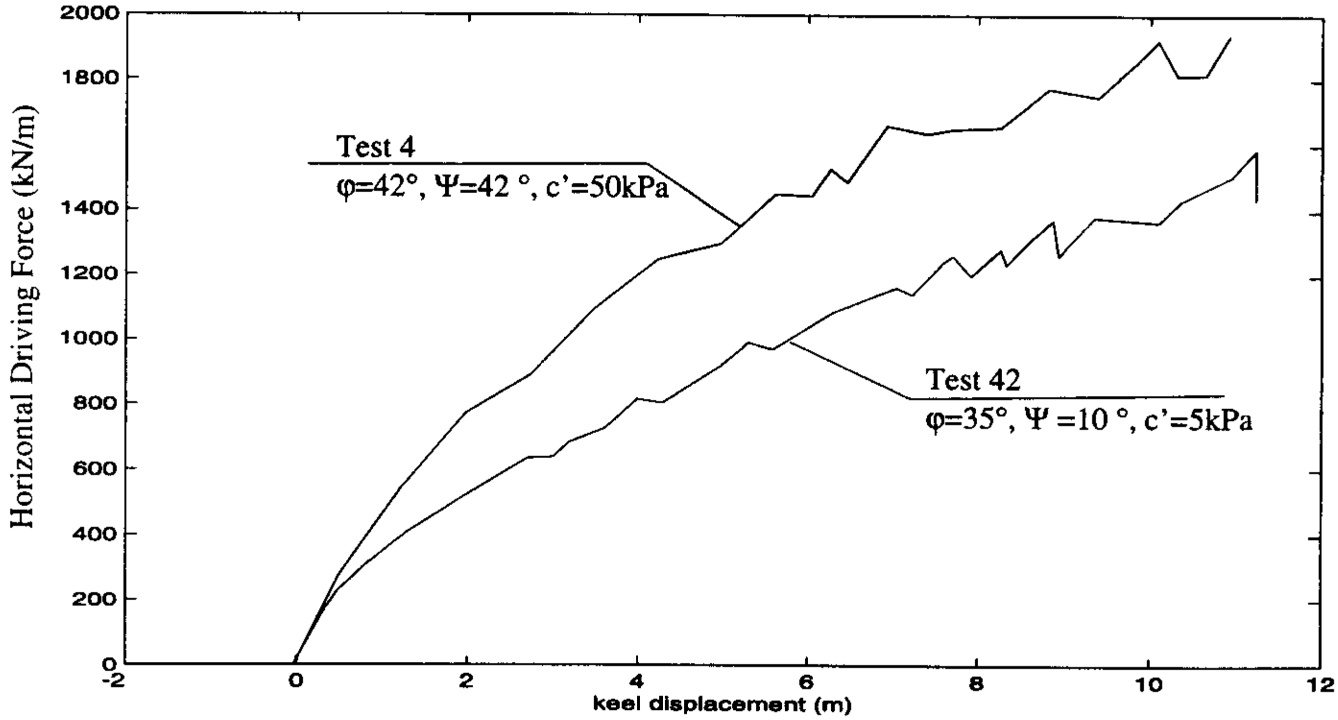


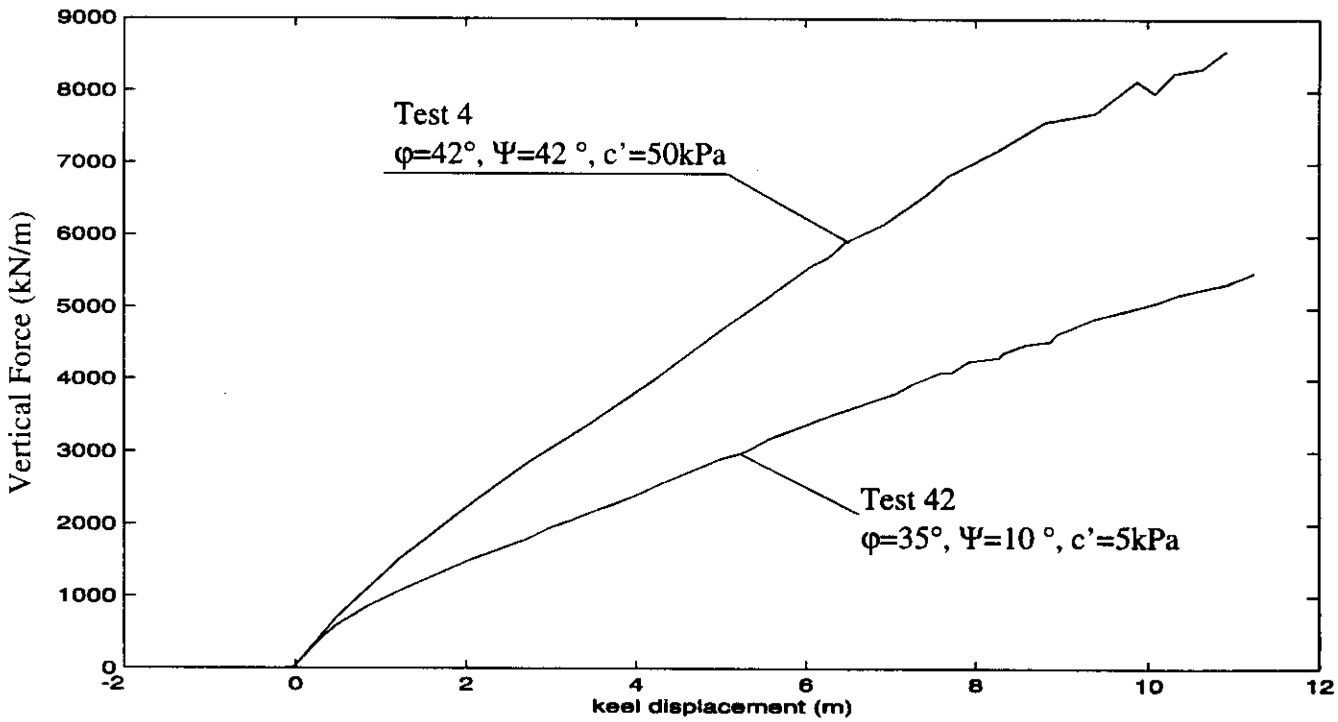


C-CORE

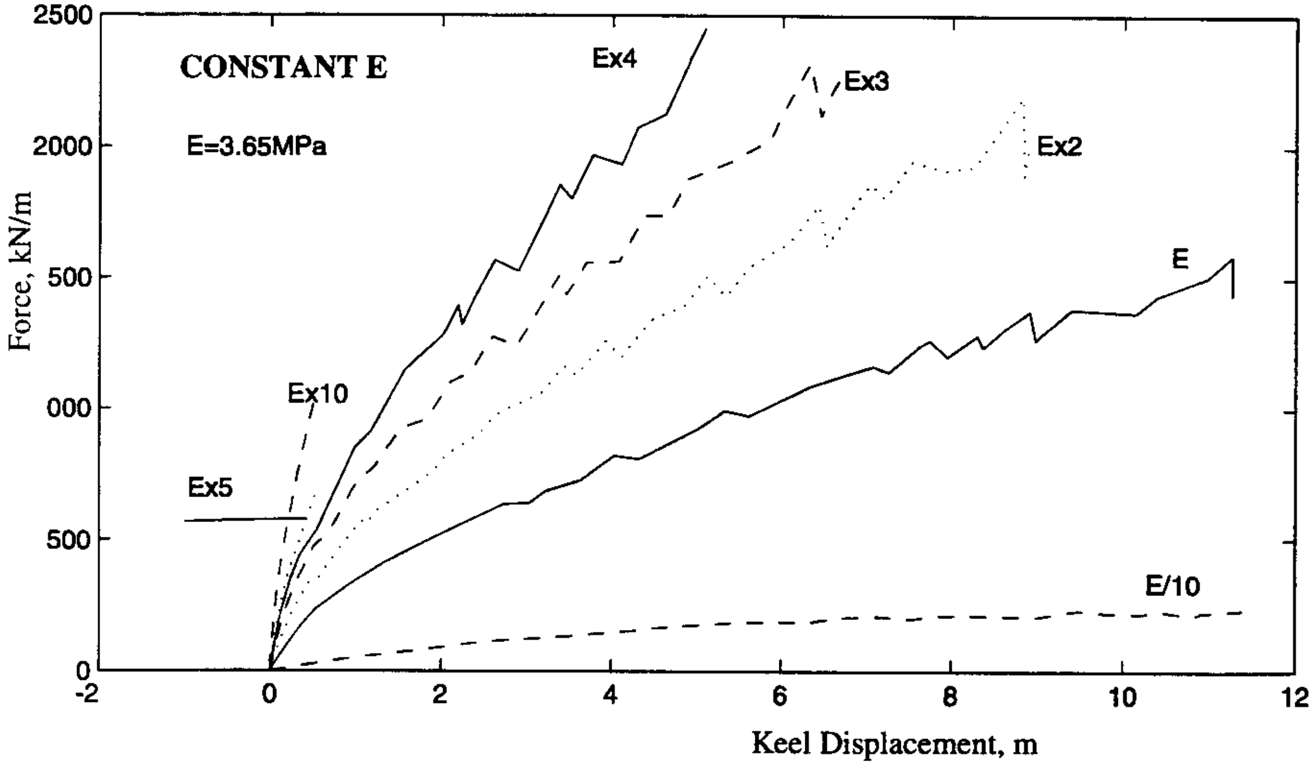
Scour Force Variation with Strength Parameters, for 0.5m Scour Depth

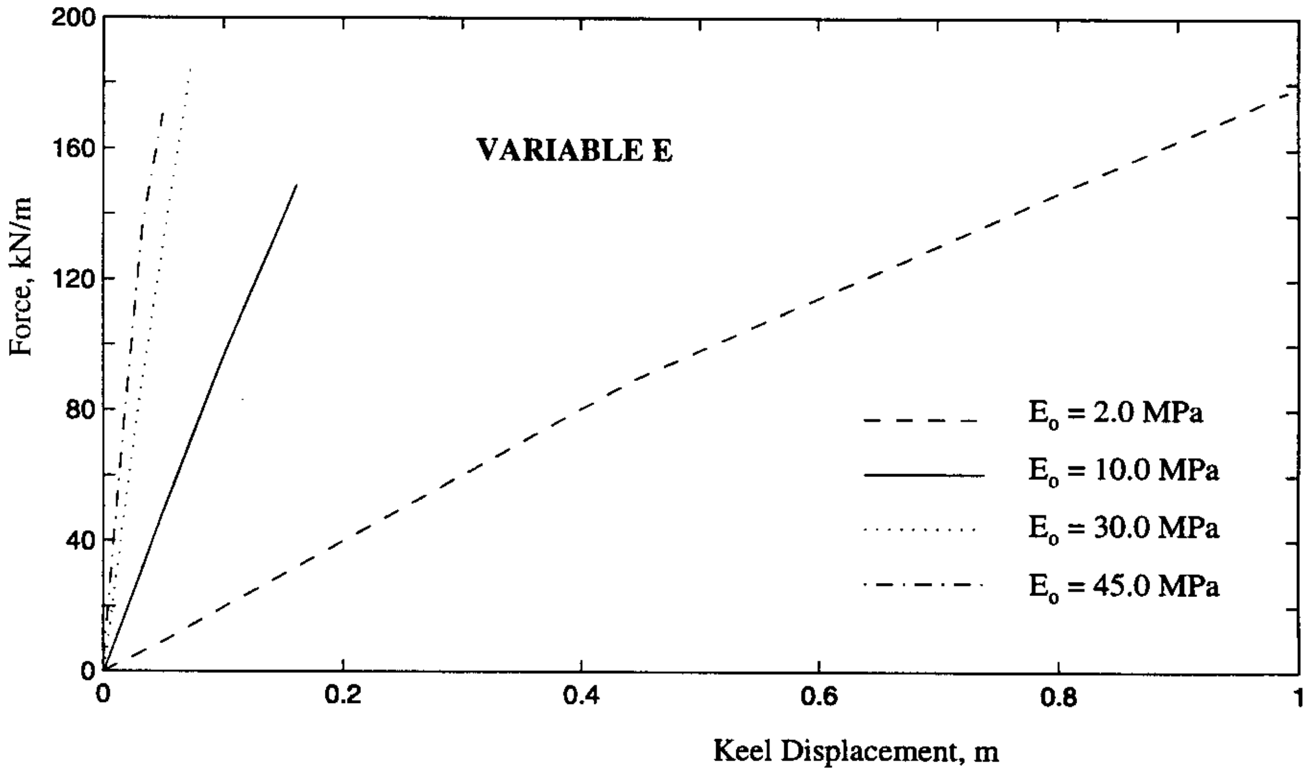
Fig. No. 6.3 6.4





C-CORE	Scour Forces Predicted for Test4 and Test42 for 1.485m Scour Depth	**Fig. No.** 6.5 6.6

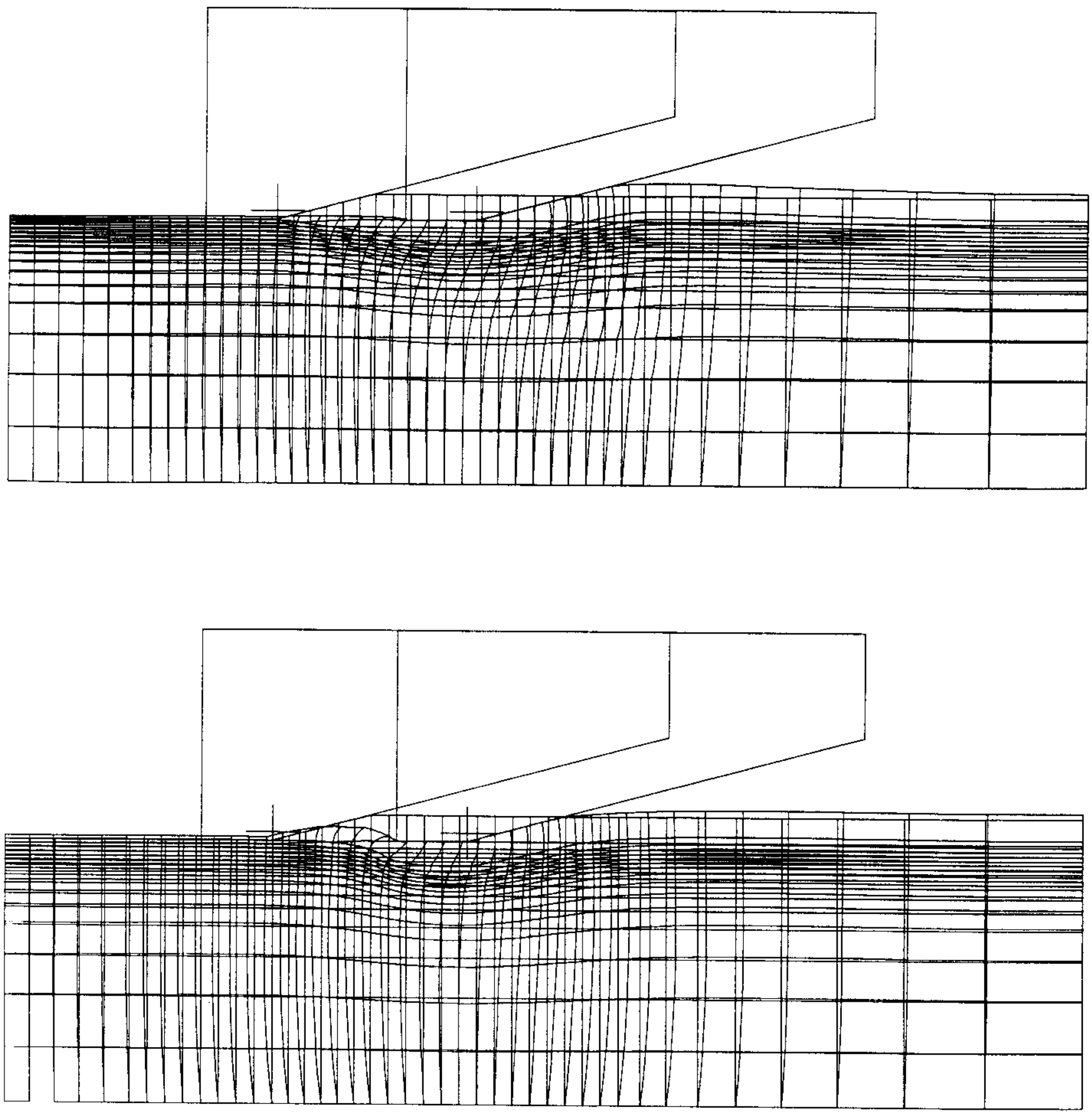




C-CORE

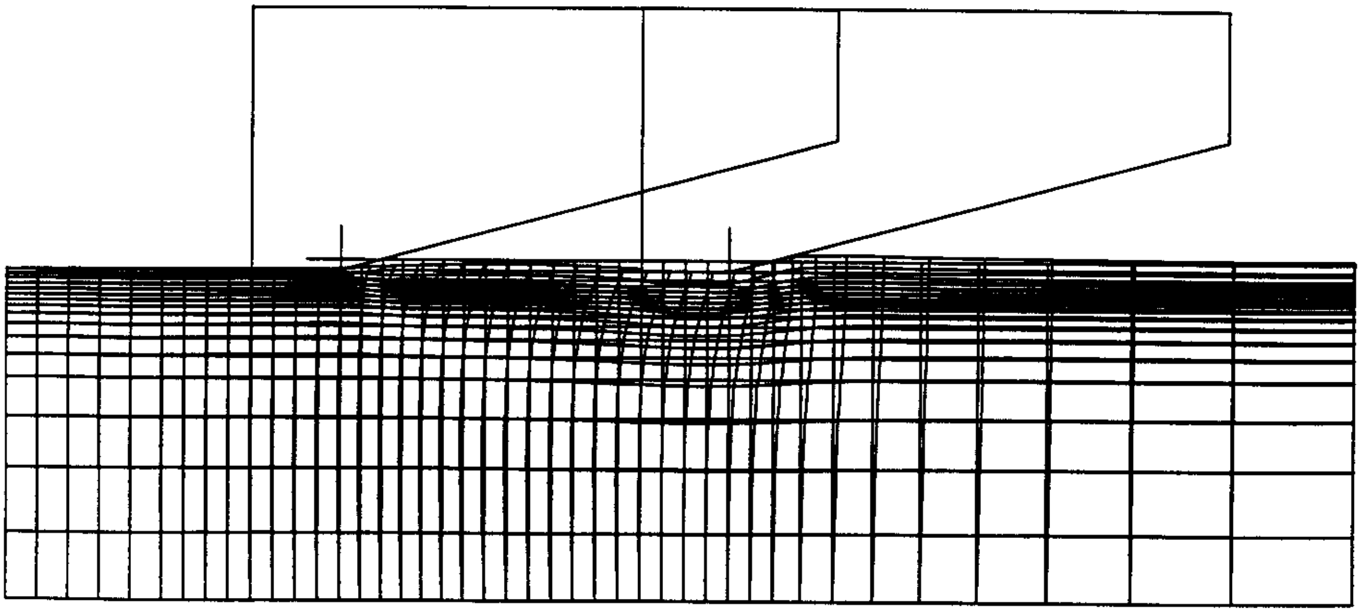
Scour Force and Stiffness Variation with Elastic Soil Modulus, D=1.485m

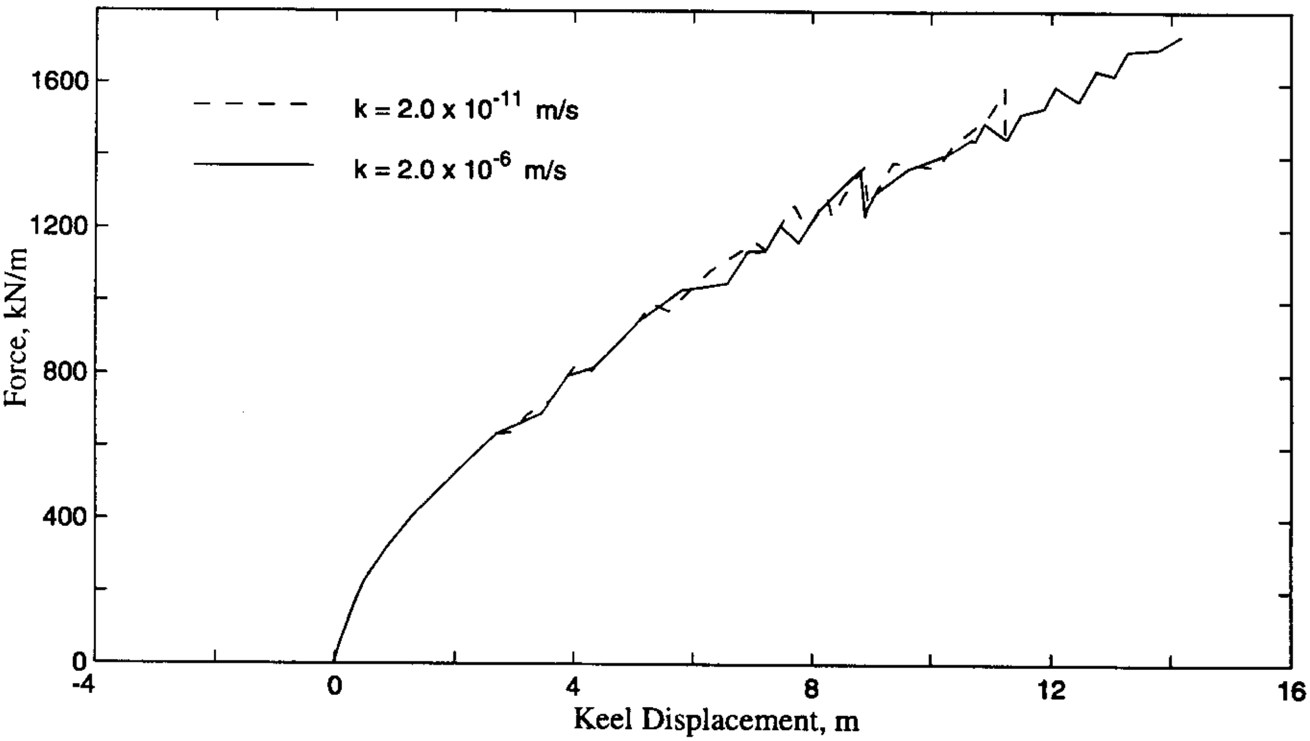
Fig. No. 6.7 6.8



Sub-scour Deformation Variation with Elastic Modulus, Tests 42 & 43, D=1.485m

Fig. No. 6.9 6.10

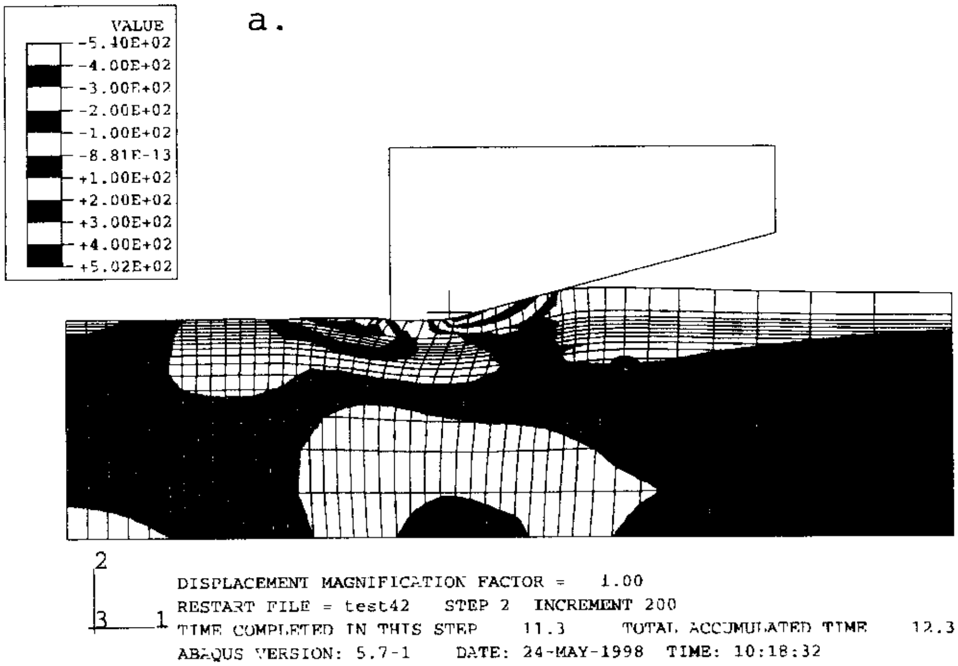


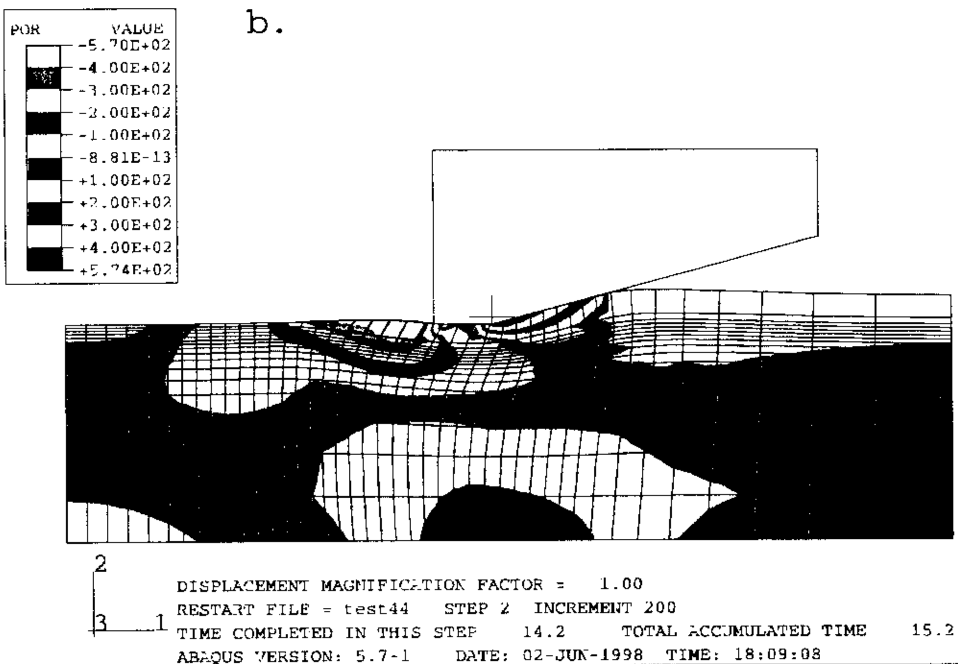


C-CORE

Sub-scour Deformations , Test D1
Scour Force Variation with Permeability

Fig. No.
6.11
6.12

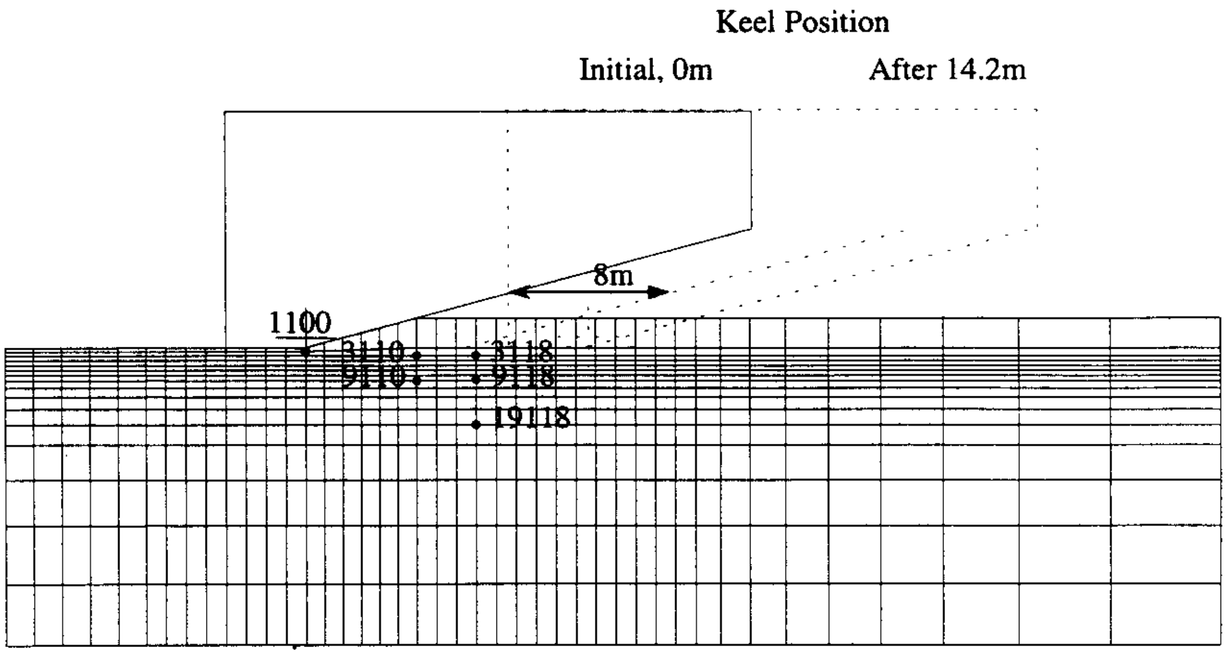


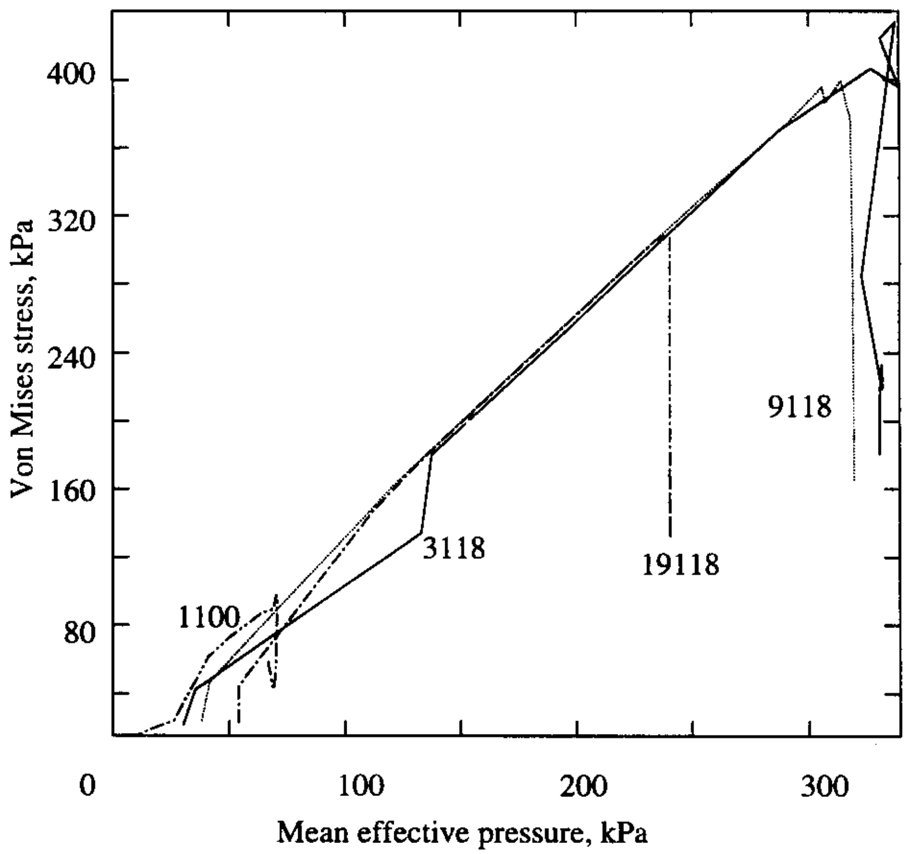


C-CORE

Excess Pore Pressure Contours, Tests 42 and 44, 1.485m Scour

Fig. No. 6.13
6.14

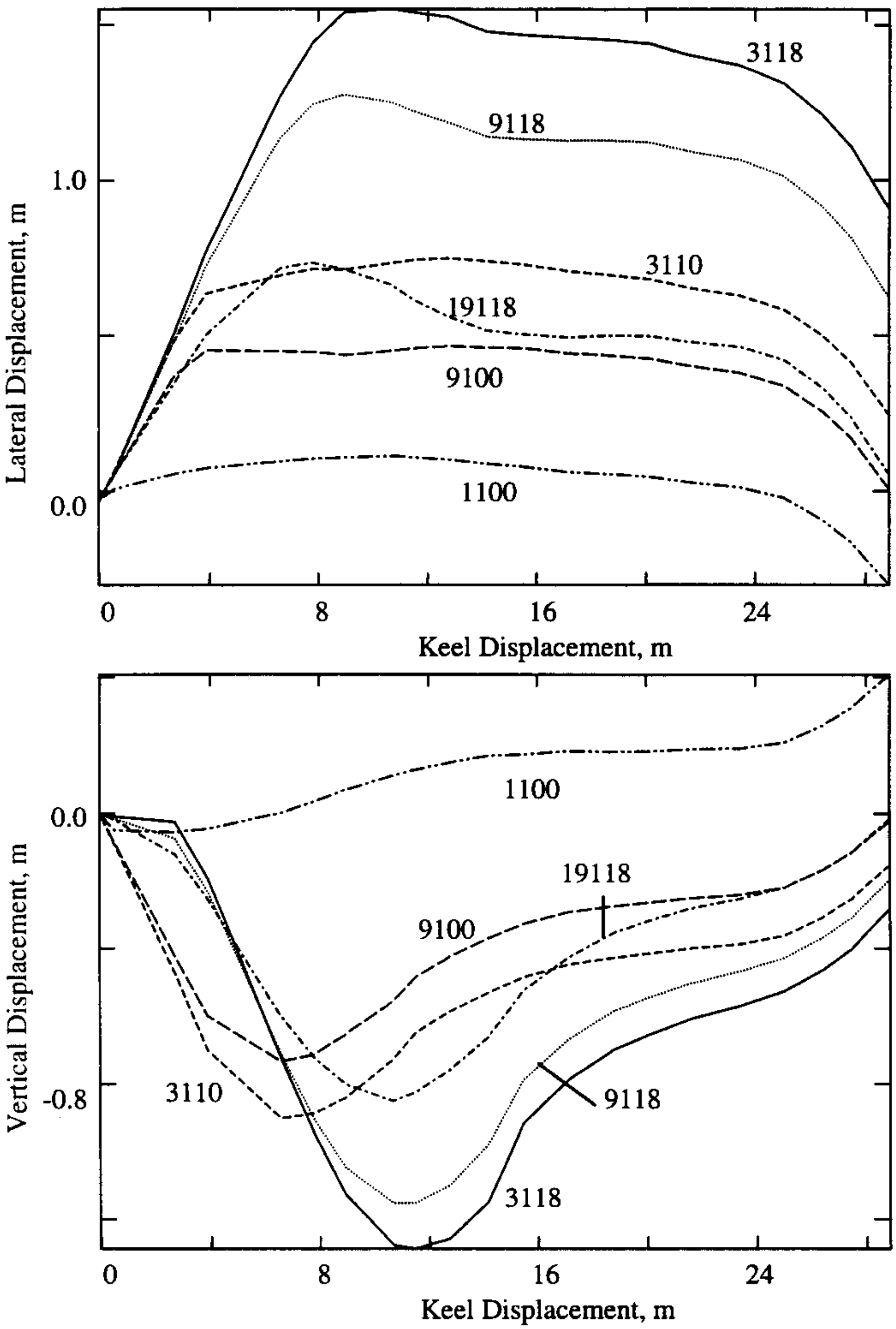




C-CORE

Finite Element Mesh & Selected Nodes and Stress Paths Test44

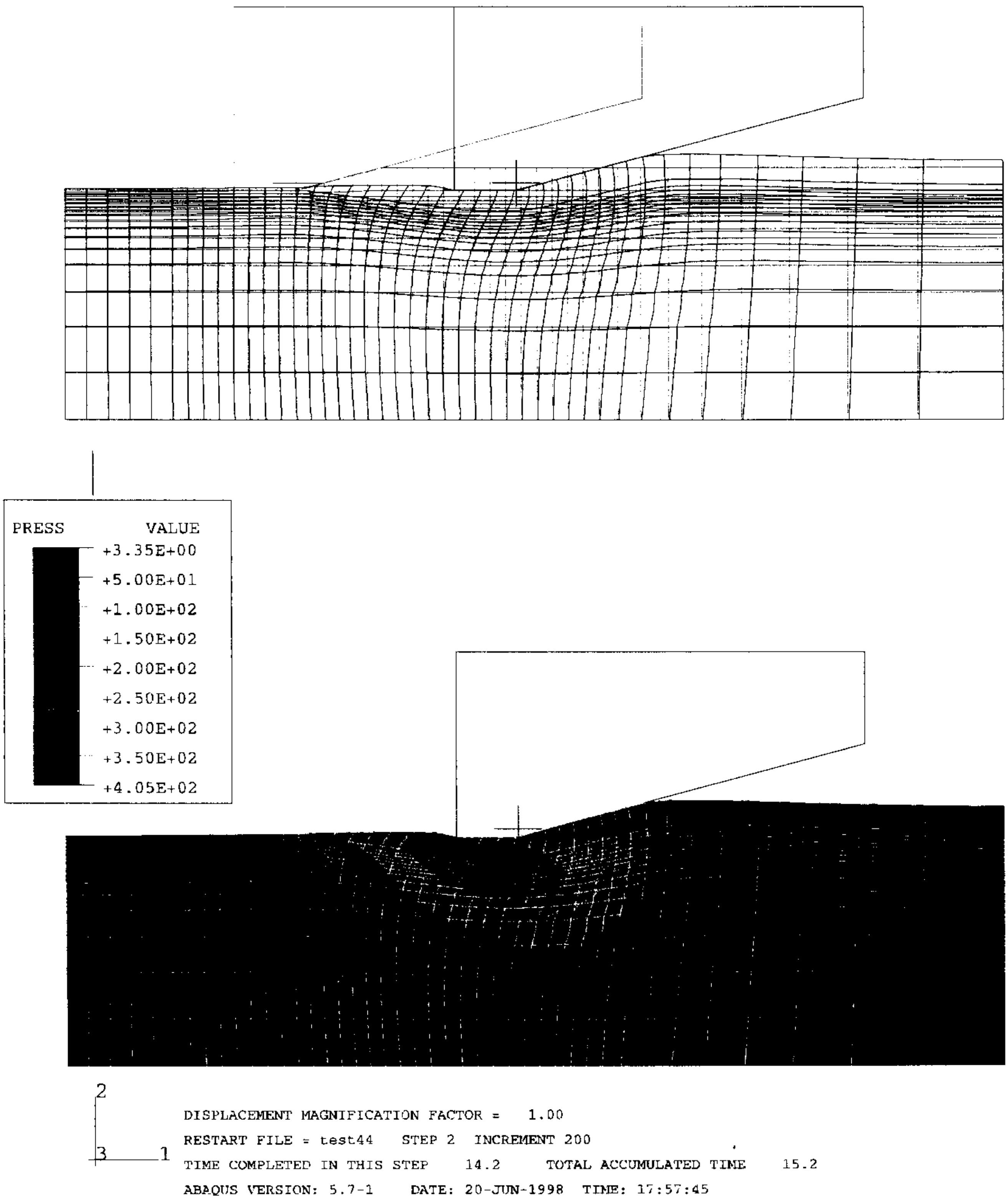
Fig. No. 6.15 6.16



C-CORE

Nodal Displacements, Test44

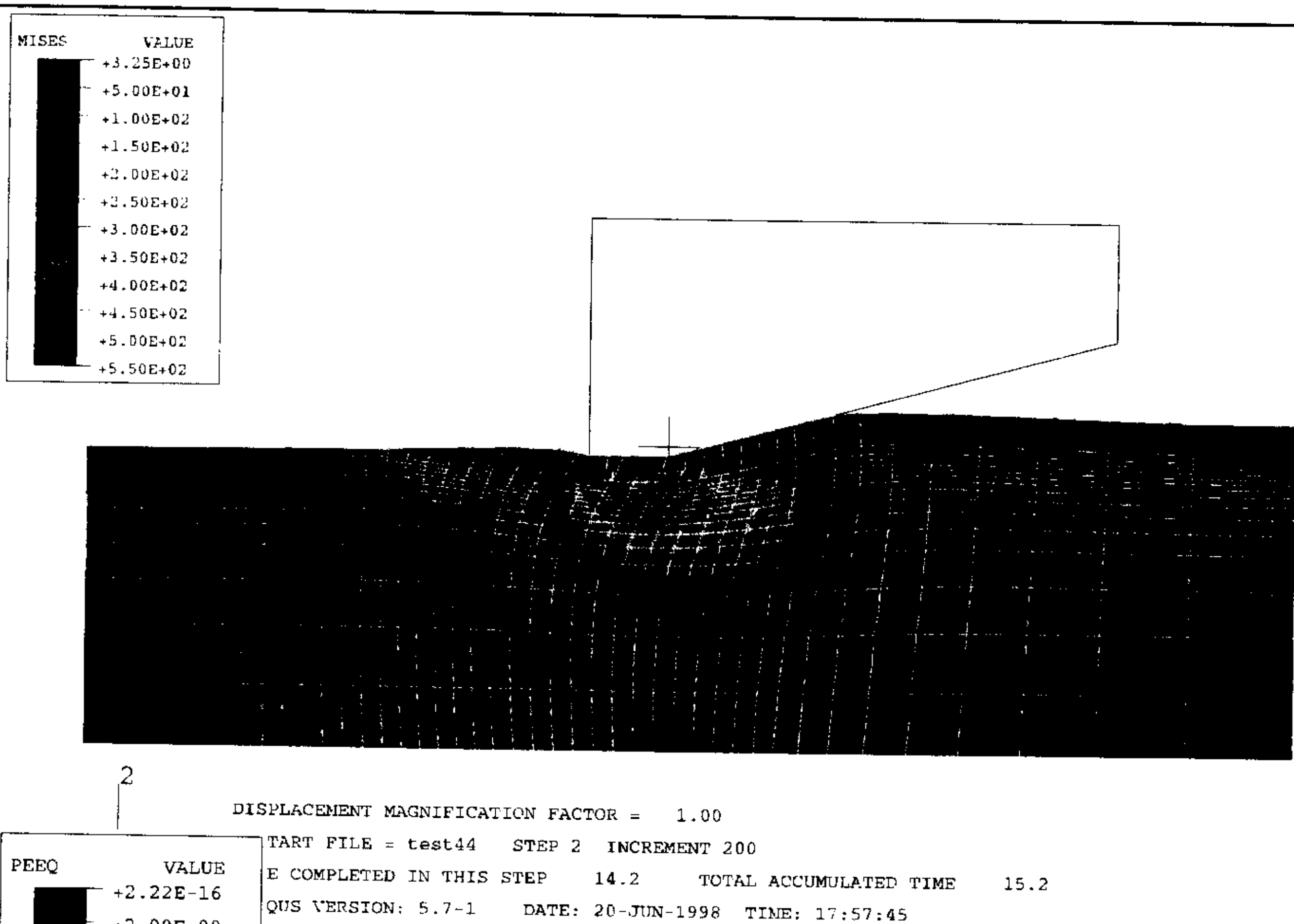
Fig. No. 6.17 6.18

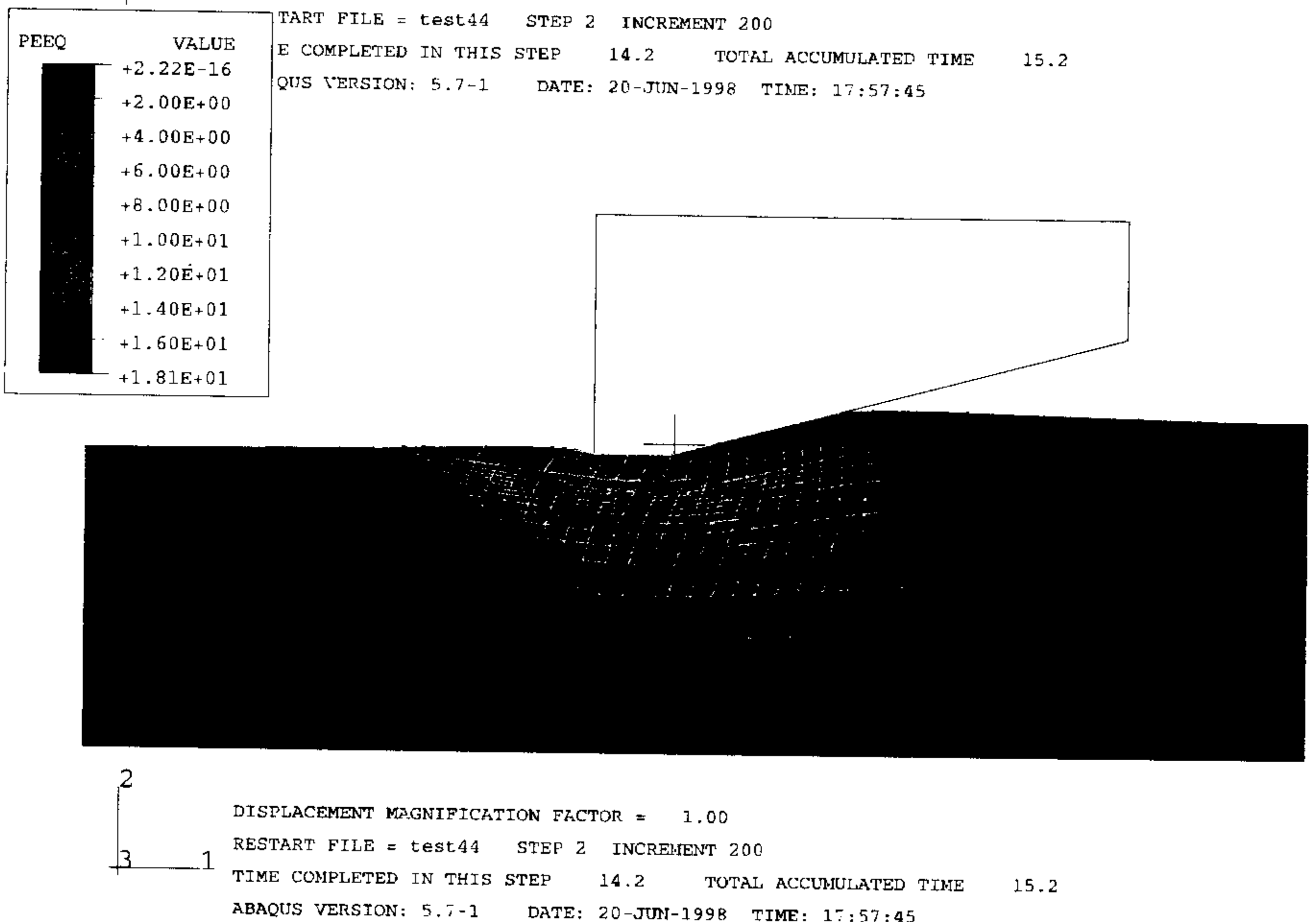


C-CORE

Deformed Mesh & Confining Pressure Contours at 14.2m Displace., Test44

Fig. No. 6.19 6.20





C-CORE

Von Mises Stress & Plastic Shear Strain Contours at 14.2m Disp, Test44

Fig. No. 6.21 6.22