ANALYTICAL AND EXPERIMENTAL MODELLING OF ICEBERG SCOURS

CENTRE FOR NEWFOUNDLAND STUDIES

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ANALYTICAL AND EXPERIMENTAL MODELLING OF ICEBERG SCOURS

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The discovery of oil and gas in the lopherg infestéd waters off the coast of Newfoundland and Labrador has generated increased interest in icebergs. There is a need to find solutions to potential iceberg hazards in order to optimize the groduction schemes. This thesis is a continuation of the ongoing research on geotechnical aspects of iceberg scours.

ABSTRACT

The searlier analytical model has been extended to incorporate the nonlinear velocity of the ideberg during scouring. This study examines the scouring potential of icebergs which rollidue to instability, increase their draft, and penetrate the seabed before scouring. For a given iceberg, if such initial penetration depth is more than a certain upper bound, only a pockmark will be left on the seafloor. For initial penetration depths smaller than certain lower bound, the resulting maximum scour depth would be as if there were no initial penetration of the seafloor.

The influence of keel shape on the maximum depth gouged by an iceberg was studied experimentally Six models of different keel shape were instrumented and pushed horizontally into a sloping send bed. The measured front face resistance for each model was correlated with the computed values using available theoretical methods. The experimental results were extrapolated to the scour model. It is shown that the influence of keel shape on the estimated scour depth is within an acceptable range of variation and thus scour depths predicted using an idealized shape are realistic.

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The notation adopted in this thesis is in confirmation to that recommended by Barsvary et al (1980). The symbols are defined at their first appearance. However,

- a list of symbols used in this thesis are given below.
 - projected area of the submerged iceberg normal to the propelling currents.
- B width of the idealized iceberg, also width of scour .
- c shear strength of cohesive soil; also cohesion of cohesive frictional soil
- C_A drag coefficient
- C, uniformity coefficient
- d depth of scour at any instant of time during scouring
- D maximum depth of scour
- D. depth of scour profile
- Edra cumulative energy due to hydrodynamic drag
- Enert residual kinetic energy of the iceberg
- Ba cumulative energy expended In overcoming soil resistance.
- F shear resistance on the bottom of trial wedge
- F' shear resistance on each side of trial wedge
- Fa-drag force on a decelerating iceberg
- g acceleration due to gravity
 - final height of surcharged soil in front of the berg
 - height of surcharged soil at any instant during scouring (obtained from the geometry of scour trench)

Salar in

- I. inside sloping length of scour track
- Ko at rest earth pressure coefficient
- $\mathbf{K}_{_{\mathbf{D}\mathbf{C}}}$ passive earth pressure coefficient due to cohesion

 K_{pq} passive earth pressure coefficient due to surcharge $K_{p\gamma}$ passive earth pressure coefficient due to weight

maximum length of scour

length of scour at any instant

maximum length of surcharged soil

1 length of surcharged soil corresponding to 1

M | mass of the loeberg

M1 rectangular prismatic model

M2 model MI with 30° inclined front face attached to it

M3 model M1 with 60° inclined front face attached to it

M4 model M1 with curved front face attached to it

M5 model M1 with cylindrical front shape attached to it

M6 model M1 with triangular wedge shape attached to it

Os outer sloping length of scour track

P soil resistance on the front face of the idealized iceberg

s initial depth of penetration

S, lower bound of S

S, upperbound of S

Ts top width of scour track

V velocity of the iceberg at any instant

V0 initial steady state velocity of leeberg (also averaged current velocity

w weight of soil in the failure wedge

Wo weight of surcharge piled up in front of model

angle of slope of the displaced soil

- w angle between tangent to failure surface and normal to wall
- β angle of slope of the seabed.
- angle of internal friction of soil.
- δ friction angle between soil and model
- $\delta_{\mathfrak{m}}$ mobilized friction angle between soil and model
- y' submerged unit weight of the ocean soil
- Yexp experimental density
- Ymax maximum dry density.
- Ymin minimum dry density
 - shear strength of soil $(\tau = c + \sigma \tan \phi)$
 - normal stress
 - saturated unit weight of the ocean soil
 - angle of the failure plane with horizontal
 - density of sea water .

CHAPTER I

INTRODUCTION

1.1 General

Icebergs drifting along the Canadian East Coast have always been of concern to the safety of merchant vessels. plying the Northwest Atlantic. Ever since the Titanic disaster in 1912, the International Ice, Patrol has been conducting studies and observations of icebergs with the primary objective of avoiding a collision with ships. However, with the recent exploration for hydrocarbons in the iceberg-infested waters off Canada's eastern and northern coasts, and the discovery of the Hibernia oil field, the iceberg problem has become more significant. Icebergs start their journey from Greenland, and drift along the Labrador Coast. Such icebergs are likely to damage offshore structures due to a direct collision or uproot buried structures such as pipelines and wellheads as a result of scouring the seabed. Instances where icebergs damaged blowout preventor stacks of exploratory wells and Transatlantic cables have been reported (Milne 1973, Duvel 1975), An estimate of the safe burial depth for seabottom structures is therefore essential. One solution to this problem is to develop an understanding of the soil-iceberg

interaction through theoretical and laboratory models. This has been one of the ongoing research topics at Memorial University of Newfoundland. The present thesis is an extension of the estiler research (Charl 1975, Green 1984) on geotechnical modelling of iceberg mecours.

1.2 Scope of this Investigation

Two approaches have been used by researchers to estimate the maximum iceberg scour depth. One method is to conduct side scan surveys and high resolution accounting profiling for a number of years and establish scouring probabilities of various depths (Lewis and Barrie 1981). This is quite expensive and time consuming. In the second approach the scouring phenomena is physically simulated in the laboratory to help develop theoretical models and predict maximum acour depth from a knowledge of the environmental parameters. The latter approach has been followed in this investigation.

The analytical models proposed earlier for determining maximum scour depth have been reviewed and the energy solution proposed by Charl (1979) is extended to take account of nonlinear velocity of scouring loobergs. Icebergs undergo continuous oblation and degradation during which small chunks of protrusions break off, rendering the berg unstable. Such bergs roll over in order to attain a new

1.1

position of equilibrium resulting in a change of the draft which in turn could cause a penetration of the iceberg into the seafloor. An expression has been developed for studying the scouring potential of such icebergs.

The experimental study in this investigation is aimed at studying the influence of iceberg keel shape on the maximum scour depth. Six different idealised shapes of the iceberg were pushed horizontally into a sloping sand bed. The total soil resistance acting on the model and the pressure distribution on the front face of the model were continuously monitored. The component of the soil resistance acting on the front face of the model in the experiment is compared with soil resistance computed from theoretical methods:

1.3 Organization of the Thesis

In chapter II of this thesis, a brief review is given of the origin and distribution of icebergs. A detailed review of the literature is presented on the analytical and experimental modelling of iceberg scours.

In chapter III a detailed description of the mechanics of scouring is given. The extended analytical model is presented and the results thereof discussed.

Chapter IV describes the experimental program of this investigation. Details of experimental facilities, test procedures and instrumentation are presented.

Chapter V contains the results of the experiments, the analysis and a comparison with the theoretical solutions.

Finally, the summary and conclusions of this investigation are presented in chapter VI.

CHAPTER II

LITERATURE REVIEW

2.1 General

The first exploratory well for hydrocarbons on the Canadian East Coast was drilled on the Labrador shelf in 1971. Sithin a decade, twenty eight other wells were completed on the Labrador and Sortheast Newfoundland shelf, many of which have confirmed the presence of oil and gas. For a proper design of the production systems, it is necessary to assess the potential hazards due to icebergs and devise suitable solutions. A summary of the literature related to the iceberg problem is presented in this chapter. The source of icebergs, their general characteristics, and their significance to the operations of the percleum industry are briefly described. A detailed review of the literature on the analytical and experimental shudy of the mechanich of securing is given followed by the presentation of the objectives of this Investigation:

2.2 Origin of Icebergs

Most of the general data on icebergs in the Northwest Atlantic have been published by the International Ice Patrol. These have been compiled and comprehensively reported by Smith (1931), Murray (1969), and Dinemora (1972) covering the aspects of the origin of icebergs, their size, altape, drift, and deterioration.

About 85 percent of icebergs reaching the Newfoundland coast, originate from about twenty one glaciers located, between Melville Bugt and Disco. Bugt on the west coast of Greenland (Fig. 1). East Greenland glaciers account for ten percent, and the remaining five percent are known to come from Northern Ellesmere Island. The glacier flow comes out of the fjords into the sea and 'calving' (i.e. breaking): of the iceberg from the parent glacier occurs due to a combination of gravity and buoyancy forces on the protruding tongue of the glacier (Smith, 1931). The icebergs. drift. along the West-Greenland and Baffin Island coasts to toin the Labrador current and move around the eastern flank of the Grand Banks before they completely disintegrate in the warm Gulf Stream. There are also several branches and deviations to this general drift pattern as shown in Fig. 1. While the number of icebergs calved at their source varies from 15,000* to 40,000 per year, the mjority of these-are trapped in the bays and coastal. indentations and only an average of about. 400 bergs reach the Grand Banks off Newfoundland. ... Fig, illustrates the variation in the number of icebergs detected annually south of the latitude 48"N.

2.3 Physical Characteristics

The size of the iceberg at the time of calving from the parent glacier depends on the mechanism of calving (Smith 1991). Icebergs longer than 1000 meters have been reported around Cape York, West Greenland (Kollemeyer, 1980). The shape of the iceberg is generally irregular and no two icebergs look alike. Even the same iceberg looks different from various angles. The International! Ice Patrol has classified icebergs based on the above water dimensions as shown in table 1, and according to the above-water shape as shown in table 2. Assuming the specific gravity of glacier ice as 0.9 and that of seawater as 1.03, the submerged volume, of an iceberg would be hearly seven times the above-water volume. However, the draft to height ratio need not be in the same propertion and is a function of the iceberg shape.

Looberga generally' deteriance in the process of their travel south. The process of melting and erosion at the water line by constant wave action causes the berge to become unerable and roll. Id. this process several protrusions of the berg may also be broken off. The drat of the iceberg could increase by as much as 50 percent (Base and becers 1984) when they roll and assume a new stable position. This periouser becomes which will be discussed in the iceberg securing process which will be discussed in a liter section.³¹



FIGURE 1 REGION OF ICEBERG PROBLEMS.



Name	m Heigh	t (ft)	Len m	gth (ft)
Tabular berg				
S - small	<6	<20	<91 ···	<300
M - medium	6 to 15	20 to 50	91 to 213	300 to 700
L - large	>15	>5ò	>213	>700
• Others				
S - small	<15	<50	<61	<200
M - medium	15 to 46	50 to 150	61 to 122	200 to 400
Ł - large	46 to 78	150 to 255	122 to 213	400 to 700
VL - very large	>78	>255	>213	>700
	and the second			

TABLE 1- ICEBERG CLASSIFICATION BY SIZE (MURRAY 1969).

TABLE 2 ICEBERG CLASSIFICATION BY SHAPE (MURRAY 1969)

Туре	Description
B – blocky	Steep precipitous sides with horizontal or flat top, - very solid berg, length/height satio 5.1.
DK - drydock	Eroded such that a large U-shaped slot is formed with twin columns or plinacles, slot extends into waterline or close to it.
D dome	Large smooth rounded top, solid type berg.
P - pinnacled	Large central spire or pytamid of one of more spires dominating the shape, lass mass than dome shaped bergs of similar dimensions.
T - tabular	Horizontal or flat topped berg with length to height ratio 5:1
Bergy bit	A mass of glacial ice smaller than a berg; but larger than a growler, about the size of a small tottage, small berg or large growler is preferred usage.
Growler	A mass of glacial lies calved from a berg or is the remains of a berg. Less than 2.5 m high and 6 m long.

2.4 Iceberg, Hazards

Because of their huge mass, even while drifting at low velocities icebergs carry enormous kinetic energy. A direct collision of an iceberg with a moving ship or a fixed offshore rig is one hazard that is well known. When the iceberg runs into shallow waters its keel may come in contact with the seabed causing long scours on the safbed. Such features have been mapped and measured extensively (Harris and Jollymore 1974; Lewis and Barrie 1991) on the Canadian Eastern seaboard during the past decade. The ploughing of the smabed by large icebergs is a potential hazard to any buried installation such as pipelines, blow out preventer stacks, and foundations.

Scouring of the seabed could also occur when an iceberg rolls over, penetrates the seabed due to a change in the draft, and then moves along causing a gouged feature on the seabed.

A review of the literature on the engineering evaluation of the problem is given below.

2.5 Iceberg Scours

There are two areas of current interest to the offshore petroleum industry where seabed scouring by moving ice features is a potential hazard. In the Beaufort Sea gouges of up to 1 m depth have been observed in wated depths up to 20 m (Barnes et al 1978). These gouges are formed by moving ice keels and the predominant propelling force is the wind action on large areas of the ice sheet. In the Labrador sea, iceberg scours have been observed in water depths up to 250 m and scour depths of 6.5 m.have been measured (Harris and Jollymore 1974) using side-scan sonars. The major: propelling force for icebergs is the drag due to the ocean currents.

There are several similarities between the ice keel scours of the Beaufort Sea and the iceberg scours of the Labrador Sea. However, the energy balance equations are different because of the difference in the type of the driving forces. The models discussed below are with reference to freely floating icebergs. But they can be easily modified for the ice keel scours.

2.6 Methods of Estimating Maximum Scour Depths

One method of evaluating maximum scour depths is to conduct side-scan and high resolution seabed surveys to actually measure the dimensions of the existing features. However, a major uncertainty is whether such features are relict and ancient or caused by recent icobergs. Annual and repetitive surveys of the seafloor is one way to delineate new and fresh scours. The amount of infilling in a scour and the effort required for repetitive surveys of the same area are the two limitations with this method. The third method which is the scope of this thesis is to develop analytical and physical models. Scour sizes can then be computed using the models for a given set of environmental parameters. The disadvantages with this method are the validation of the model to the real scours, the scale effects, and the accuracy of the input parameters. At this time, it would seem appropriate that all the above methods are to be pursued and attempts made to integrate them in a suitable field program. A flow chart of such an approach (Lewis and Benedict 1981) is shown in Fig. 3.

2.7 Analytical Models

The earliest attempt to analyse the sopuring phenomena was by Chari and Allen (1972). They idealised the ideberg as a rectangular priam moving normal to a sloping bed of cohesive sediments of very low strength. The berg was assumed to plough the seabed without uplift, overcoming the passive resistance of the soil developed on the front face and the adhesive resistance on the base and sides. By equating the kinetic energy of the iceberg to the work done in ploughing, an equation was obtained. By knowing the initial kinetic energy, keel width of the iceberg, the slope of the seabed and its average shear, strength affection de the maximum scour depth can be obtained from this theory.



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Refinements to this model have been made by considering the influence of surcharge on the total soil resistance (Chari 1975) and the effect of curtent drag on the scouring icaberg (Chari and Muthukrishnalah 1978). Chari and Grean (1981) examined the effect of side friction on the iceberg for scours in cohesionless soils.

Lopez et al (1981) formulated a differential equation for the velocity of a scouring iceberg by balancing the forces of inertia and current drag with the soil resistance. In order to delineate the hydrodysamic drag effects in the estimation of maximum scour depths. However, for analytical convenience; the soil resistance and the soil model were approximated in this formulation.

Foundation Engineering Company of Canada. (FENCO) developed a variety of models for the Arctic Petroleum Operators Association (APOA 69-1, 1975) for different types of ice scours. These models can be classified into two broad categories, estimation of the scour depths due to ice ridges in the shallow water region of the Beaufort Sea and the estimation of scour depths due to large sized ice blocks such as the shallow and icebergs.

The first model designated by FENCO as the Dynamical Solution is a generalized model and can take into account the influence of the initial kinetic energy and environmental forces such as winds, waves, currents, and pack
ice forces on the acouring potential of the ice mass. The ice mass is a rectangular prism floating in water with three degrees of freedom, surge, heave, and pitch. Three equations of motion using three equilibrium equations were formulated considering inertial forces due to motion and hydrodynamic forces, gravity, buoyancy and soil resistance under the influence of the driving forces. From the known initial conditions, these equations were solved using the 4th order Runge-Kutta method. The soil resistance consists of the frontal passive earth pressure, base reaction and the side friction. The base reaction was calculated using elastic. plastic and elasto-plastic methods. Results presented were restricted to Beaufort Sea conditions. This analysis shows that the scour track is very much undulated in contradiction to smooth variations observed in scour surveys. Selection of a proper soil model in determining the base reaction seems to be crucial in obtaining numerical stability of the solution .-

The energy solution presented in the APOA report 65-1 (1975) is very similar to that of Chari and Allen (1972). The only minor differences are the inclusion of the side friction of the soil, and the method of determination of the frontal resistance. The sum of external forces due to wind, wave, current and pack ice was equated separately to the total soil resistance of the soil at the end of the arour.

It was concluded that for the Beaufort Sea conditions, the influence of pack ice force predominates and is much larger than the effect of kinetic energy. A good agreement between the results of the energy, model and that of the dynamic model was reported for Beaufort Sea conditions. However, none of these models have been verified experimentally.

2.8. Experimental Studies and Physical Models

As mentioned estiler, the baic mechanism in iceberg scouring is the dissipation of the kinetic energy in doing work against the soil resistance and according to will established principles of conservation of energy. However, there are several practical difficulties in physically modelling the phenomenon to laboratory scale. One major problem is to scale the soil strength and other related properties. It has been argued (Charl 1980) that the energy belance meeds no physical Verification and the only apportmental verification required would be for the geotechnical aspect of the enalytical model.

Chari (1975) designed a titable glass sided tank 3.6 milong; 0.75 m wide and 0.7 m deep to prepare 1:10 slopes of silty clay. Several experiments were conducted using 230 mm wide ployiglass prismatic models. Significant qualitative observations were also made in this study

regarding the failure phenomene of soil and other geotechnical aspects of interest which formed the basis for subsequent and also current investigations. Quantitative measurements included the measurement of the total necessary to push integer models of three different into the sloping bed, the pressure distributions on all the faces of rectangular primmtic models and also at some locations in the soil bed. The influence of velocity of the inceberg on the total soil resistance was examined and found to be negligible. The measured soil resistance was correlated with the calculated static passive soil resistance using Coulomb's trial wdge analysis and correlated with the theoretical scour model.

The Arctic Petroleum Operators Association (APOA) commissioned a project in 1980 op the experimental study of iceberg scours (Abdelnour and Lapp 1980). A total of 110 expariments were conducted using two fectangular primmatic models (witch 520 mm and 260 mm) and an inverted square pyramid with a cone angle of 54 . These models were pushed at three velocities into saturated flat bads of sand, silt and clay with three different depths. Data on soll resistance in both vertical and hofizontal directions of motion, pressure distribution on the model front face and also in the soll, and the shape characteristics of the scour profile were collected. The result were presented in the

dimensionless form proposed by Schuring and Tmori (1964). Contrary to the generally accepted theofree in geotechnical engineering, it was suggested by Abdelhour and Lago (1980) that the verticity of the iceberg has an influence on the total soil resistance even in cohesionless soils.

Green' (1984) conducted experiments in a 14 m x 3 m x 1 m soil tank with dry sand. Based on the measurements of total soil resistance in the direction of motion and the pressure distributions on the front and sides of a 500 mm wide rectangular prismatic model, it was concluded that the contribution of side friction and base friction to the total soil resistance was negligible. It was also reported that the influence of the iceberg velocity was negligible and the total resistance was proportional to model width. The importance of iceberg keel shape in determining the total soil resistance was demonstrated and further testing with different keel shapes was recommended. Tests were also conducted with a pipeline model of 122 mm diameter. The model was instrumented with pressure transducers and burried at several depths in the sand bed below the maximum scour in order to delineate the zone of 'sediment movement below the scouring berg.

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2.9- Geotechnical Models for Soil-Iceberg Interaction

The purpose of the physical models in iceberg scour. studies is to understand the soil-iceberg interaction. The effect of the keel shape is one of the parameters identified in previous investigations. This will be examined further in the experimental work and discussed in Chapter V. Although there are several good publications in the geotechnical literature on passive soil pressure, most of these are for cases of relatively small wall movements and for vertical or nearly vertical surfaces. The geotechnical research topic nearest to the phenomenon of iceberg scours is the movement of bulldozer blades in soils. Even here, there are several differences, such as the sloping soil surface, the large amount of soil surcharge in front of an iceberg, and the three dimensional shape of the berg. Nevertheless, all the relevant and available theoretical methods will be used in analyzing the experimental data. The simple theoretical methods suggested by Coulomb (1776), Terzaghi (1943), Shields and Tolunay (1973), Rosenfarb and Chen (1973), and Harison (1973) are reviewed below.

The limit equilibrium solution of Coulomb assumes a shear plane inside the soil starring from the toe of the retaining wall. By considering horizontal and vertical forces on the wedge (Fig. 4) the force on the wall can be computed. The critical failure plane is that which requires a minimum horizontal force. The assumption of plane means sufface is not a generalized condition. A large error is associated with the Coulomb's method when the angle of wall friction is graster than one third the angle of internal friction for the soil (Terasgifi 1943). In such cases, a curved sufface of failure is to be considered.

The sliding surface can be assumed as a logarithmic spiral (Terzachi and Peck 1967)., In the logarithmic spiral method, (Fig. 5), the spiral starting at the toe smoothlyjoins the Rankine's failure surface which is inclined at an. angle of 45° - 6/2 to a major principal stress direction. Within the mass of the soil represented by ad, c, the state of . stress is the same as that in a semi-infinite deposit in a general passive Rankine state. The shearing stresses in this zone on planes bisecting the failure planes are zero., Therefore, the passive earth pressure on the plane f, d, can be calculated from the simple Rankine's solution. By the nature of the assumed failure surface, the regultant of the soil resistance F on the portion bd, of the failure surface. passes through the center of logarithmic spiral. The entire . process is to be repeated many times by varying the position of the center of the logarithmic spiral on the line d.a and its extension. The failure surface which gives the minimum computed resistance is considered as the critical failure surface.

2:

Shields and Tolunay (1973) suggested a procedure to calculate the passive earth pressure coefficients which is similar to the logarithmic spiral method. However, there is no need to search a failure surface in this method. From a knowledge of the stress conditions at the soil-wall interface, the angle of the fangent to failure surface g at the toe of the wall can be determined which then gives a specific location for the center of the spiral and hence the entire failure surface. The soil mass to be analyzed is bounded by the vertical wall, the spiral, and the principal plane, which is a vertical gassing chrough the intersection of the logarithmic spiral and Rankine's failure plane. From-Mohr's circle of stress at the bottom of the wall, the angle of failure surface was calculated to be:

 $s_{\psi} = \frac{1}{2} \left[\operatorname{arc. cos} \left[\operatorname{cos} d(\psi - \delta) - \frac{\sin (\psi - \delta)}{\tan \psi} \right] - \psi - \delta \right] \left[1 \right],$ where s_{ψ} is the angle between failure suptace and the normal to the wall as shown in Fig. 6. The mass to be analyzed was divided into vertical slices and the horizontal and vertical equilibrium of each slice was matisfied. In doing so, it was

assumed, that all vertical shear force in the zone was concentrated in the slice next to the wall.







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Harrison (1973) proposed a method to analyze the ultimate load capacity of an inclined rigid interface linearly translating into a soil in a specific direction. Harrison (1973) developed this method basically to analyze the plate drouser problem in agricultural engineering. This method is similar to the Shields and Tolunay (1973) method in the sense that there is no need to locate a failure surface. Shields and Tolunay (1973) assumed that the full angle of friction was mobilized at the moving wall which is justified. when large displacements are allowed. The compatible failure surface is determined using Mohr's diagram. Harison (1973) assumed that the direction of the failure surface coincides with the direction of translation of the wall, and the mobilized friction angle, would be restricted to maximum soil-structure contact friction. Evidence for this assumption was shown by photographing the failure phenomena. when inclined plates were pushed horizontally into the soil. The failure mechanism according to this 'theory is shown in Fig. (7). The equilibrium wedge abc which forms on the interface ab must move horizontally along with the model and ac becomes the failure plane making the required angles (90+*) with the extension of the line bc. The interface ac is treated as a perfectly rough retaining wall and the earth pressure is calculated using the logarithmic spiral method. The pole of the spiral is located at a; ad and ac are the

radii of the spiral. The resultant force thus calculated was used to compute the earth force on the model when the horizontal and vertical egulibrium of the wedge abc were satisfied.

Chen and Rosenfarb (1975) used the upper bound technique of ilmit analysis to obtain passive limit earth pressures: They followed the method of superposition which states that if a failure mechanism is described by n independent parameters, the passive pressure acting on the right wall can be expressed as:

 $P = \frac{1}{2} \gamma H^2 \min K_{p\gamma}'(\theta_1, \theta_2 - - \theta_n)$

qH min K_{pq} ($\theta_1, \theta_2 - - \theta_n$) + CH min K_{pq} ($\theta_1, \theta_2 - - - \theta_n$) +

where $K_{p\gamma}$, K_{pq} and K_{pc} are pure numbers representing the effects of weight, surcharge and cohesion respectively. For cohesionless soils the third term is neglected. Closed form expression for earth pressure coefficients can be derived using upper bound technique of limit analysis method in terms of soil parameters and independent parameters of the failure mechanism. When these expressions are minimized with respect to parameters (9., $8_2 - - 9_n$) and used in the above squation, the passive earth resistance P per meter length of the wall can be obtained. Several failure mechanism



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composed of rigid bodies and radial shearing zones were considered. The mechanisms considered by Chén and Rösenfarb (1973) and the variation of the results obtained there are given in Fig. 8 and Table 3. It was concluded that the twotriangle mechanism and log-sendwich mechanism gave better respires and also had a limited number a parameters to be minimized.

2.10 Objectives of the Present Investigation

From the literature review, it my be concluded that the energy model is quited simple and offers good correlation with other models. The model assumes that the scour formation is gradual, earting from an initial touch down by the iceberg. It has been reported (Lewis and Barrie 1981) that several pock mark features have been observed in the région of iceberg scours. It has also been shown (Bass and Peters 1984) that the draft of an iceberg could increase, as a result of tolling. It is possible that such bergs could pierce the seabed if the water depths were less than the increased draft and cause a local depression on the seaflor. As "an extension of the theoretical model of Chari (1979) it was decided to examine the effect of an initial seabed penetration by avcolling iceberg and the resulting shape of the scourt rack. As part of such a theoretical study. At was

also decided to evaluate the nonlinearity effects of the current drag on a decelerating iceberg during scouring. This part of the study is an extension to that done by Lopez et al (1981).

It has been shown exclise (Chari 1975, Green 1984) that the frontal shape of the iceberg model has an effect of the measured forces. However, the results have not been quantified. As part of this investigation, the experimental study consists of quantifying the influence of the frontal shape of the iceberg on the total soil resistance and hence a the computed scour size. The tasks in this investigation can be stated as:

 To modify the analytical model for estimating the maximum scour depth using the principles of conservation of energy (chari 1979) and considering the nonlinear velocity of the scouring (cebers (Lopez et al 1981) to account for hydrodynamic drag forces during scouring.
To extend the analytical model to compute the scouring potential of an iceberg which fenetrates the scaled due to instability (Bass and Peters 1984).

To experimentally verify the effect of the frontal shape of the keel on the soil resistance by horizontally punking six different shapes they a sloping bed of sand and measuring the total soil resistance and pressure distribution on the front face along the length of scour-

 To correlate the measured front face soil resistance with computed soil resistance from available theoretical methods.

. To incorporate the effect of the iceberg keel shape in the analytical model.

3

CHAPTER III

ANALYTICAL STUDY

3:1 General

The analytical model for iceberg scouring published in the literature is that of Chari (1979) in which the seabed is assumed to be a weak cohesive sediment and the scour depth is obtained using the principle of energy balance. This model will be estimined further in this chapter and will be extended to include the effect of nonlinerity of the iceberg deceleration, the presence of frictional soils, and the effect of initial seabed penetration by an iceberg before scouring.

3.2 Mechanics of Scouring

The drift of an iceberg, particularly those with large drafts, is primarily due to ocean currents. Under steady-state conditions, the drift velocity can be taken as the velocity of the current averaged over the draft of the iceberg. There is no net hydrodynamic drag under such steady-state conditions. For purposes of analysis, iceberg scouring may be visualized as one of the variations or y combinations shown in Fig. 9. In the first case, the botto of the iceberg touches the seabed and rides along a hard surface, grounding in a short distance due to the transformation of kinetic energy into potential mergy. No visible sour marks are likely to be loft on the seabed in this process. In the second mode, which represents another extreme condition, the looberg comes in contact with very weak seabed soil and scours the seabed through a horizontal ploughing action. A long and deep scour mark is likely to be left on the sea floor. The third mode shown in Fig. 56 is a combination of the above two modes in which the iceberg forms a scour track and is like aubjected to an uplift.

Icebergs are known to become extremely unstable due to the process of continuous melting and frequent breaking of portions of the iceberg. If is vary common Tor icebergs to rotate due to this instability and to assume a new position of equilibrium with a different wireff. It has been suggested by Bass and Peters (1964) that iceberg drafts could increase by as much as 50% when they roll and feorient to a more stable position. During such a process; it is possible that the iceberg could penetrate the seabed and then cause a long scour (Fig. 94). This phenomenon, which was not considered in previous research, is now gramined and discussed in this thesis.

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3 . 3 Iceberg Scour Model

When an iceberg scours into a gentle slope, the soil scooped out will initially pile up in front of the iceberg. As the scouring continues, ridges will be formed on either slds of the track. The idealised concept of iceberg acouring (Chari 1979) is shown in Fig. 10, in which it is assumed that the friction between the iceberg and the soil can be neglected because of the low strength of soil and the presence of a thin film of melt water around the iceberg. Thus the resistance to iceberg movement is primarily the frontal remistance on the scouring face. For iceberga scouring in soft and wask meabed sediments, the energy of the iceberg was equated to the work done by soil remistance in ploughing action and the resulting equation of energy balance was expressed (Chari 1972) in the form:

$$\frac{1}{2} MV_0^2 + \int_0^2 F_d dt = \int_0^2 P dt$$
 [3]

where:

= mass of the iceberg

/ = initial steady-state velocity of the iceberg (also

velocity of currents)

= drag force on a decelerating iceberg

= length of scour at any instant

= maximum length of scour

berg

= soil resistance on the front face of idealized

For cohesive soils, the soil resistance P at any

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 $P = \frac{\gamma' (h+d)^2 B}{2} + 2 cdB + \sqrt{2} cd^2$

here:

Y' = submerged unit weight of soil .

 h = height of surcharged soil at any instant during scouring (obtained from geometry of scour trench)
d = depth of scour at any instant

= width of idealized iceberg

c = shear strength of cohesive soil

The soil shar strength c varies over a vide range for terrestrial soils and the variation is even greater for sea floor soils. Eublished data of shear strength for marine soils (indersen 1976) show a range of values from nearly zero up to about 500 kPa in the 5 m depth sone below the Mulline. At the Hibernia site and its vicinity, the surficial sediments are solum dense to dense sand and a shear strength in the range of 100 kPa has been generally used (Russell and Muggeridge 1981) as the typical value for purposes of computations. A range of 25 - 100 kPa for shear strength of the sende has been used in this thesis.

On the left side of Eq. [3], the first term is the steady-state kinetic energy of the iceberg when it is moving without any relative velocity between the ocean currents and the scouring iceberg. The second term of Eq. [3] represents the energy due to the effect of the curtents on the loeberg during the scouring process. The drag force on a decelerating iceberg can be expressed as:

$$F_{d} = \frac{1}{2} C_{d} \rho A |V_{o} - V| (V_{o} - V)$$
 [5]

where:

C_ = drag coefficient >

p' = density of water

A = projected area of the submerged iceberg normal to the propelling current

= instantaneous velocity of iceberg

and the other terms as already defined.

In the above expression, the coefficient C_d can vary from 0.5 to 2.0 depending on the shape of the floating bdy (Bureau Verlkas 1975) and for bodies in contact with the seabed; C_d may be multiplied by 1.4. Banke and smith.(1974) measured drag coefficients of 1.2 during situal towing of small icobergs. Mountain (1980) has used a drag coefficient of 1.5 for icobergs of all sizes and shapes. Shirasawa et al (1984) measured drag coefficients warying from 0.63 to 0.91 in laboratory models. If a drag coefficient of 1.0 is assumed as a typical value for purposes of distussion, the corresponding kinetic energy due to the added mass component will be in the order of 4.5 (Framed and Chari 1984). The consequent influence due to the effect of this added mass on, the scourt depth computation is negligible and hence not identified separately in Eq. [5].

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From Eqs. [20] [4], and [5], the maximum scour depth and length in cohesive soils has been expressed as:

$$\frac{MV_{0}^{2}}{2} + \frac{C_{d}\rho ALV_{0}^{2}}{6} + \frac{Y'(H+D)^{2}}{6} + cDLB + \frac{72}{3} + cD^{2}LB = [6]$$

" L. Tan f

where:

maximum scour depth corresponding to maximum scour length L

= slope angle of the seabed

and the other terms as already defined ..

The above equations were defined on the assumption that the iceberg velocity decreases linearly from a maximum of $\int_{0}^{0} at$ the commencement of acouring and theoretical curves of maximum acour depth were developed (Chari 1979). A parametric analysis of the effect of different variables was presented by Chari and Peters (1981). Equation [6] will be examined further in the following sections.

3.4 Iceberg Velocity During Deceleration

 Lopez et al (1961) examined the hydrodynamic drag on decelerating iceberge during grounding and concluded that the effect is an important component in the propulsion of icebergs during scouring and in computing the maximum scour degines. It was also concluded that the gouge length would be overestimated by 11% at worst, by assuming a linear welocity during deceleration. The conclusions are valid for the simplified soil model assumed by Lopez et al (1981) in which the soil resistance was assumed to be directly proportional to the equare of the depth. It may be seen from Eq. [6] that several factors such as the density, soil strength, depth of penetration, and seabed elope influence the soil resistance. The effect of these factors are to be taken into consideration in calculating the soil resistance.

The velocity variation of decelerating icabergs can be obtained numerically in incremental steps instead of considering a continuous function as done by Lopez et al (1981). The residual kinetic energy of the iceberg (E_{net}) at any instant may be obtained knowing the initial kinetic energy of the iceberg (KE), the cumulative energy expended in overcoming the soil resistance (E_g) and the cumulative energy added due to the hydrodynamic drag (E_{drg}) . This can be expressed as:

 $E_{net}^{l} = KE - E_s + E_{drg}$

 $\frac{MV^{2}}{2} = \frac{MV_{0}^{2}}{2} - \int P dt + \int \frac{\sigma_{d} P A |V_{0} - V|}{2} dt$ [9]

Equation [9] can be solved in steps till the velocity V is nearly zero indicating that the iceberg has

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[8]

come to rest and the gouging process has been completed. Figure 11 is the flow chart for the computer programme (Appendix A). The velocity profile obtained from this iceberg motion as given by Eqs. [3] and [8] is a better representation than the assumption of a linear velocity variation. For the purpose of the parametric analysis, ranges of values were assumed as shown in Table 4 and the results are discussed below.

Figure 12 shows the velocity variation for an iceberg of 10 x 10⁴, Kg (10 million took) during grounding as obtained using 80. [8] and [9]. The cumulative energy driving the 'Laberg into' the soil, the work done by the soil realstance, and the convergence of these too at the end of the scour are also shown in the figure. It is obvious that the computed velocity profile deviates from the straight. Now. The estimates of scour length using the nonlinear velocity profile are greater by about 12% for the values of the parameters shown in Fig. 12.

The velocity profile and the drag force were computed for a typical 10 x 10⁹ kg (10 million ton) isoberg for different drag coefficients and the results are shown in Fig. 13. The nonlinearity in the velocity variation is more pronounced for lower drag coefficients and the variation tands to be linear for higher drag coefficients. A similar effect noticed for the drag force is also shown in the figure. Fig. 14 shows the effect of shear strength on the computed maximum scour depths. The maximum scour depth decreases with increasing shear strength which is to be expected and the results are similar to those published earlier (Chari and Peters 1981). However, the assumption of a linear profile for the velocity will result in an underestimation of the scour depth in the order of 118 for a lo x 10⁹ kg (10 million tch) iceberg.

A similar comparison for the effect of the varying seabed slope (Fig. 15) shows that the assumption of linear velocity would overestimate the scour depth for a steeper seabed and will underestimate the value in flatter slopes. The difference in the computed results would be about 23% at worst. It may be observed that the seabed slope has virtually no effect on the scour depth computations for larger irrebergs when the nonlinear velocity variation is considered.

The analysis of the effect of the coefficient of drag (Fig. 16) on the scour depth computations shows that the calculated scour depth are more sensitive to the variation in the drag coefficient than previously reported by Charl and Peters (1981). It can be seen that the assumption of linear velocity variation results in an overestimation for lower drag coefficients and an underestimation at higher drag coefficients.







TABLE 4 RANGE OF PARAMETER VARIATION

		and the second se
PARAMETER	STANDARD REFERENCE VALUE	RANGE OF VARIATION
14		
Iceberg Mass (M)	10 x 10 ⁹ kg	10 ⁹ - 25 x 10 ⁹ kg
Drift Velocity (V	o) 1.0 m/sec	0.2 - 1.0 m/sec
Keel Width (B)	20 m	10 - 30 m
Drag Coefficient	(c _d) 1.0	0.5 - 2.0
Seabed Slope (Tan	β) 1:500	1:100 - 1:1000
Soil Shear Streng	th (t) 100 kPa	25 - 100 kPa
Angle of Internal	Friction ()	20° - 40°
Unit. Weight of So	11 (x) 15 kN/m ³	4 1 <u>1</u> 1.



FIGURE 12 ENERGY AND VELOCITY VARIATION WITH SCOUR LENGTH

. .







FIGURE 15 EFFECT OF SEABED SLOPE ON SCOUR DEPTH

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similar comparison is made in Fig. 17 for the effect of varving scour width on the sensitivity of gouge depth computations. The extended model gives scour depths which are up to 16% higher than earlier computations. It is, thus concluded that while the assumption of a linear velocity variation during scouring is a good first approximation, the true, velocity profile is nonlinear. The actual deviation in the computation, of scour depth is dependent on the combination of the other environmental variables.

3.5 Effect of Soil Type

Generally, surficial scaped sediments are cohesive and underconsolidated and the first attempt in modelling iceberg scours was for such soils. However, the surficial sediments are not universally the same. For example, in the Grand Banks region where the Hibernia oil field is situated the seabed is made up of predominantly sand and gravel. For a general soil with cohesion and friction, the soil resistance P as given by Eq. [4] has to be modified by. considering Coulomb's trial wedge (Fig. - 18). The force P can be expresses as:

> $(W_{O} + W) \sin(\theta + \phi) + (F + 2F') \cos\phi$ cos

COB (& + A -

weight of surcharge at any instant

=
$$\gamma'B \frac{1}{2} \frac{d^2 \cos\beta \,\cos\theta}{\sin(\theta - \theta)}$$

shear resistance on the bottom of wedge

 $\frac{B d \cos\beta}{\sin(\theta - \beta)} c$

hard

shear resistance on each side of the wedge (negligible for icebergs of larger widths)

$$\left\{ \begin{array}{c} \frac{1}{2} \cdot a^2 \frac{\cos \beta \cos \theta}{\sin(\theta - \beta)} \right\} \quad \left\{ c + K_0 \left\{ \frac{\gamma \cdot d}{3} \right\} \\ \frac{W_0 \sin(\theta - \beta)}{B \cdot d \cos \theta} \right\} \quad tan \phi \\ \end{array} \right\}$$

= coefficient of earth pressure at rest

= 1 - sine (Jaky 1948)

and the other terms are as defined earlier.

A critical angle 0 of the failure wedge is obtained by minimizing P with respect to 0. The approximation in assuming a plane failure surface is justified as long as $\delta < 9/3$ (Terzaghi 1943). The friction at the soil-lockerg interface may be assumed to be a minimum because of the continuous presence of the meltwater. The value of P as obtained from Eq. [10] can be incorporated in the energy balance Eq. [3] and thus the scour dimensions can be computed for any type of eashed soil. This is an extension to the solution proposed earlier by Charl (1979) for purely cohesive materials. The influence of the angle of internal friction of the soil on the scour depth computations $h = 1000 \text{ m}^{-1}$ (19. By comparing Fig. 14 and Fig. 19 it can be seen that the maximum scour depths obtained in cohesionless materials with friction angles in the range of 25 - 40°, are somewhat undrained shear strengths in the range of 25 - 100 kPa. Kivisild et al (1982) have given an energy solution for ice keel grounding which is compared with the present solution. The scour depths obtained using the model proposed here are higher (Fig. 20). This is due to the additional hydrodynamic effect during socuring which is considered in the present model and also the different techniques for computing the soil resistance."

3.6 Effect of Initial Seabed Penetration

Icebergs are subjected to continuous ablation in the process of which they gain equilibrium. In such a condition even a very small perturbation such as the initial contact of the iceberg with the seabed of the breaking of a small protrusion of the iceberg would cause it to roll with the possibility of penetration into the seabed due to an increased draft (Fig. 9d). Assuming that the iceberg will then prove horizontally, the volume of the scooped out soil may be equated to the volume of the scooped out soil frontal such are such any instant can be obtained from Fig. 21.

and expressed as:

 $2K_{11}^{2}I_{1}^{4} + 4K_{111}^{2}I_{1}^{3} + (2K_{11}^{2}I_{1}^{2} + 3K_{11}B \tan \alpha)$

- $3l^3B$ tang tang - $6l^2BS$ tang = 0

where:

 $K_1 = l_1(\tan \alpha + \tan \beta)$

1, = length of, front surcharge at any instant

 α,β = slopes of surcharged soil and seabed respectively

Γ11

S = initial depth of penetration

and all other terms as diready defined The above equation is similar to that derived by Chari (1975) except that the scour trench in this case has an initial depth. At any scour length 1, the front face soil resistance in cohesive soils can be obtained by slightly modifying Eqn. 4 and written as:

 $P = \frac{x' (h + S + \chi \tan \beta)^2 B}{2} + 2C \left[S + \chi \tan \beta \right]^2$ all the terms are as defined earlier . [12]

An equation of energy balance similar to Eq. [7] can be obtained as:

 $\frac{w_0^2}{2} + \frac{c_d \rho A w_0^2}{6} = \frac{r' (B+B+Ltang)^2}{6} \frac{(S+Ltang)}{Lang} + \frac{r k [S+Ltang]^2}{Lang} + \frac{r' 2}{3} \frac{c(S+Ltang)^3}{Lang} - \frac{r' (K_2^2 S+S)^2 g_B}{6 Lang} - \frac{g_B}{2} \frac{g_B}{2} - \frac{r'}{2} - \frac{g_B}{Lang} - \frac{r'}{2} \frac{(S+Ltang)^2}{Lang} - \frac{r' (K_2^2 S+S)^2 g_B}{Lang} - \frac{r' (K_2^2 S+S)^2 g_B}{Lang$

where:

. tang + tanβ)

S + L tans

and all other terms as already defined.

Equation [13] was evaluated numerically and the scour dimensions computed for different values of the environmental parameters.

Figure 22 is a typical result for the standard reference values shown in Table 4. It is seen that there is an upper bound S_u for the initial penetration depth corresponding to each iceberg size for a given set of parameters. From the figure, it may be seen that the iceberg will gouge the sea floor after piercing, if and only if the initial penetration is less than this upper bound. If the penetration is greater than this S_u , there will be no perceptible further scouring. In such a case, there is likely to be a pockmark formed on the seabed. This phenomenon is consistent with the observation of Lewis and Barrie (1981) wherein actual pockmarks have been noticed on the ocean floor. The upper bound may be identified in Fig. 22 by locating the points where the curves of initial penetration tend to become horizonterl.

It may also be seen from Fig. 22 that the maximum scour depth is not affected by initial penetrations less than a certain lower bound \mathbf{S}_1 . For initial penetration below this bound, the maximum scour depth will be as if there were no such initial penetration. Envelopes of these upper and lower boundW are shown in Fig. 22. Such envelopes may be established for any given set of parameters.

With increasing initial depths of penetration, the contribution of energy due to hydrodynamic drag effect is reduced. This may also be deduced intuitively as the soil resistance soon after penetration is directly proportional to the penetration depth. Thus, with increasing initial penetration, the iceberg will come to a stop after a shorter travel.

The above effect on the computed sour depths is shown in Fig. 23 from a slightly different perspective. It is seen that increased shar strength decreases the maximum sour depth which is to be anticipated. However, the magnitude of the soil shear strength has no influence then the initial depth of penetration is larger than the critical depth. Similarly, if the soil shear strength is less than a certain value corresponding to a given initial penetration, the depth of penetration has no influence on the maximum scour depth. The existence of such critical depths is also demonstrated in Fig. 24 in which the effect of iceberg drift velocity is shown. The upper and lower bound penetration depths are thus unique to a given iceberg.

From an extension of the analytical model, it has been shown that the velocity of an iceberg during seabed gouging is nonlinear. However, its effect on the accuracy of the computations depends on the other parameters. It has been shown that one can establish upper and lower bounds for

initial penetration of the seabed by capsizing icebergs for . purposes of computing further scouring of the seafloor.

The related physical model tests and results are discussed in the following chapters.





FIGURE 19 VARIATION OF SCOUR DEPTH WITH ANGLE OF INTERNAL FRICTION

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FIGURE 22 SCOUR DEPTH FOR DIFFERENT ICEBERC SIZES AND INITIAL SEABED PENETRATIONS

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FIGURE 23 VARIATION OF SCOUR DEPTH WITH SHEAR STRENGTH FOR VARIOUS INITIAL SEABED PENETRATIONS

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FIGURE 24 VARIATION OF SCOOR DEPTH WITH VELOCITY AND INITIAL SEABED PENETRATION CHAPTER IV.

4.1 General

The plytical model described in the previous chapter cannot be duplicated in its entirety in the laboratory due to limitations in scaling the soil grain size and shear strength (chari 1973). The analytical model is based on two main principles; energy balance and soil-iceberg interaction. The concept of energy balance needs no verification in the laboratory. The analytical model would be fully perified if the soil-iceberg interaction can be physically modeled. Any physical modelling of iceberg scours will thus be a partial, newstreless a walld model.

The earlier studies by Charl (1975) were conducted in a tiltable, glass-sided flume with 23 cm (9") wide plexiglass instrumented models and in clays of 1,10 slope. Green (1984), conducted tests in medium sand with 1:35 slopes and 500 mm wide models. The present investigation is an extension of those model tests.

4.2 Experimental Facilities

4:2.1 Towing Tank

The towing tank is 14 m long, 6 m wide and 0.8 m deep and has a central longitudinal dividing wall as shown in

Fig. 25 and 26. "The towing carriage is fabricated out of two parallel hollow rectangular beams over 6 m ing length and spaced at a clear distance of about 1.3 m with suitable crass beams. The beams are ballasted with steel reinforcing bars to provide a counter-weight of 14 kN in order to resist the overturning moment while scouring. The area between the two beams is covered by metal grillage and the area serves as working space for the instrumentation. A variable speed 7.5 H.P electric motor & ransmits power through a torque converter to a 62 mm diameter shaft spanning the length of the carriage. The sprockets at each end of the driving shaft are connected to the sprockets of the supporting wheels by a chain. The carriage movement is controlled by press type switches for both forward and reverse directions. addition to these, limit switches are provided at the two ends of the carriage rails to automatically stop the carriage at a safe distance from either and of the tank.

4.2.2 Iceberg Models

Most of the earlier experimental studies (Charl, 1975, Abdelnour and Lapp 1980, Green 1984) have been with primatic models with some limited testing of non-prismatic shapes. These studies have shown that the shape has an effect on the total soil resistance and recommendations have been made to further investigate the shape effect.



FIGURE 25 PLAN AND CROSS SECTION OF TOWING TANK (GREEN 1984)

10.0



FIGURE 26 A GENERAL VIEW OF THE TOWING TANK, CARRIAGE AND MODEL

REFERENCE	DESCRIPTION	SIDE VIEW (mm)	TOP VIEW (mm)
MÌ	RECTANGULAR	600	-1000 →
S.W	RECTANGULAR PRISM WITH 30° INCLINED PROFILE	-1000	
М3	RECTANGULAR PRISM WITH 60° INCLINED PROFILE	603	<u>•−1000</u> 500
м4	RECTANGULAR PRISM WITH CURVED-PROFILE	300 300 300	500
8 8	RECTANGULAR PRISM WITH Cylindrical front shape	600	500
M 6	RECTANGULAR PRISM WITH WEDGE TYPE FRONT FACE	600 •	45

FIGURE 27 VARIOUS SHPAES OF THE ICEBERG MODELS TESTED

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FIGURE 28A RECTANGULAR PRISMATIC MODEL



FIGURE 28B MODEL WITH A KEEL SLOPING AT 30°



FIGURE 28C MODEL WITH A KEEL SLOPING AT 60°



FIGURE 28D MODEL WITH A CURVED KEEL



FIGURE 28E MODEL WITH A CURVED KEEL DURING SCOURING



FIGURE 28F MODEL WITH A CYCLINDRICAL SHAPE DURING SCOURING



FIGURE 28F WEDGE-SHAPED MODEL



FIGURE 28H MODEL WITH A RANDOM SHAPE



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FIGURE 281 MODEL WITH A RANDOM SHAPE (NOTE THE FAILURE WEDGES, SIMILAR TO THOSE FOR THE RECTANGULAR SHAPE)



FIGURE 28J SHAPE OF THE SCOUR TRENCH AND RAISED SHOULDERS



In addition to the rectangular prismatic model, five other different shapes were used in this investigation. These are shown in Fig. 27 and 28. The various frontal keel shapes were fabricated with 6 mm aluminium sheets and bolted to the front face of the existing rectangular model.

The rectangular model is connected to a tidid mounting frame (Fig. 29) by means of thin swing plates with a width alightly less than 500 mm. The mounting frame, together with the iceberg model, can be lifted with a gulley block hanging from the roof and placed at any desired elevation relative to the sand bed. Before starting the tests, two load cell holders were screwed into the threaded holes of the mounting frame such that the horizontal force exerted on the iceberg model is transmitted to the two load cells. When the load cells are positioned there is no telative displacement between model, frame and tow carriage. The swing plates were arrong emough to eliminate the rotation of the model under an uplift force and also flexible endugh

4.2.3 Soil Bed

As briefly mentioned in the literature review, published data on geotechnical properties of sea floor sodiments on the Canadian East coast are very scarce. However, from the limited information available, it can be seen that the seabed material Ng the scoured ateas can vary from soft cohesive soils to sand and boulders. Chari (1975) conducted model tests in saturated silty clay slopes of 1:10. Green (1984) used dry cohesionless sand of 1:35 slopes for tests with the 500 mm wide models. Abdelnour & Lapp (1980) used level soil surfaces of clay, silt, and sand under saturated conditions. . However, tests in sand do not necessarily have to be under saturated conditions because of the easy drainage in cohesionless soils. From considerations of ease of handling, experiments for this investigation were conducted in dry sand. The use of dry sand offers the additional advantage of exposing the surcharge, the failure surface, and the scour track all of which can be visually observed and measured. About 18 m of dry cohesionless sand with grain size distribution shown in Fig. 30 and the properties listed in Table 5 was laid at a slope of 1:35. The maximum grain size of the sand is 4 mm which compares well with the 11 mm diameter pressure transducer surface. The method of preparing a consistently uniform sand bed and density calibration will be described in a later section.

4.3 Instrumentation

One of the objectives of this investigation is to measure the total load necessary to tow the iceberg model and the pressure distribution on the front face of the iceberg model. The schematic of the instrumentation is shown in

82 1000-0 Sizes Clay 100.0 HYDROMETER ANALYSIS Coarse Medium Fine Sizes 10.0 SIEVE SIII - Millimetres ō Fino 40 60 100 Sizos Modium -Sand Grain Conrse ۰ Sizos 01. Solve --Sizes 2 Gravel S S S : S Finst 5 P20 0 00 0 2

SXPERIMENT 1112 CURVE GRAIN SIZE DISTRIBUTION

TABLE 5 PHYSICAL PROPERTIES OF SOIL

Soil Type	Brown, Well Graded Sand with Traces of Silt.
Maximum Grain Size	4.75 mm
Effective grain size	0.065 mm
Coefficient of Uniformity	6.9
Coefficient of Curvature	1.23
Relative Density of Grains	2.68
Minimum Dry Density	, 1706 kg/m ³
Maximum Dry Density	2049 kg/m ³
Experimental Density	1733 kg/m ³ ±28
Density Index	0.13
Angle of Repose	37° ± 2°
Molsture Content	0.22% (Air Dry)
Angle of Internal Friction	35.5*
	and the second

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FIGURE 31 SCHEMANIC OF THE INSTRUMENTATION USED IN THE EXPERIMENTS

Fig. 31. Quartz plezo-electric load cells and pressure transducers were used in this investigation. The manufacturer's specifications for the sensors and their re-cellbration procedures are given in Appendix 8.

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The pressure transducers and the load colls were connected to Dual-mode amplifiers (Model 5045, Kistler Instrument Company) through low noise transducer obles. The D.C. voltage output from the amplifier was fed as an input to 8 channel Hewlet Packard Magnetic Tape Redorfer.

To locate the relative position of the carriage at any instant during the test, a metal vice was structed along the length of the tank by the side of a fixed metar tape and, a b.c. voltage of 3 volts was applied at tits ends. The potential difference measured between one end of the vice and an aluminium slider fixed to the carriage was continuously measured and recorded as the carriage moved from one end to the other. The reading on the meter tape at the beginning and the end of the scour provided a cross check on the length of the scour. A two pen X-Y plotter was used to play back the recorded readings.

All the recording instruments were placed on custom . built work benches on the top of the carriage and suitably protected from dust.

4.4 Test Procedure

The complete test procedure can be divided into four parts. A major portion of the test was devoted to the preparation of the sloping mand bed. The second part was cleaning of the instruments and connecting them together. After these pre test preparations; running the test and retrieving the data was routine. Post scour observations included density verification, measurement of scour dimensions and surcharge build up. Sach process is described in detail in the following paragraphs.

4.4.1 Preparation of the Sloping Sand Bed

The volume of the sand involved in this test is about 18 cubic meters. When the volume of the sand involved is small, techniques such as a raining method, vibrofloatation, fluidisation are normally used to obtain a test sample of uniform and consistent density. In view of the large quantity of sand involved in this experiment, after trying several methods, it was decided to adopt a simple raking technique to prepare the sand bed everytime. After studying different sizes of takers, (Green 1984) suggested a simple four pronged take of about 500 mm width that can be attached to the tow carriage (Fig. 32). Abdelnour and lapp. (1980) used a take similar to a farmer's harrow.

The method used by Green (1984) was used in this study with some slight modifications. Air dry sand was placed in the tank at an approximate slope of 1:35 with a thickness of about 0.2 m near one end of tank increasing to about 0.6 m at the other end. Two angle sections were fixed to the side walls of the tank on the inside at a slope of 1:35 as a guide to form the surface of the sloping sand bed.

Before starting the soil preparation, the leeberg model, along with the mounting frame was unbolted from the towing carriage with the help of the pulley block, and the model was placed at a higher, elevation on wooden blocks resting on the carriage. This avoided the interference of the iceberg model with the sand bed while it was being taked.

Proparation of the said bed stafted with shovelling the sand and forming an approximate Sloping surface. The towing carriage was then positioned as near to the start of the tank as possible, and a trench of about 300 mm was dug just in front of the forward carriage beam. After moving the take supports to the prelaid paint markings, the take was olded to the studs. Running the tow carriage up and down the tank fixed about a 0.6 m wide track of the soil plong the. length of the tank. The take was then moved to the next position and the procedure was topeated until the entire upper layer was mixed leaving a strip of 0.3 m width on both sides of the bed which served as a working space. The level of the raker was then brought down to the lowest pair of bolts on the rake supports, and the bottom most layer was raked. This resulted in a thorough mixing of upper lavers which were subjected to more disturbance due to scouring in earlier experiments and reasonable mixture at the bottom layers where least disturbance is expected. In total, the tow carriage was moved twelve times up and down the length of tank for complete mixing of the sand bed. After raking, a wooden bar was placed across the width of the tank, on the sloping guide beams fixed to the inside of the walls. Any soil required in the central portion of the width was supplied with a shovel from the shoulders and the excess material was removed by dragging the wooden bar on the sloping guide beams along the length of tank thus obtaining a smooth bed of reasonably uniform density. This procedure was consistently followed throughout this investigation. The undisturbed average density of this bed was obtained with a hand penetrometer which was calibrated using the same sand rained at different densities in'a drum.

4.4.2 Data Recording

The process of preparing the soil bed raises lot of dust and some effort was needed to clean the working area on: the tow carriage as the piezd-electric sensors. Charge amplifiers and microdot connectors are sensitive to dust. The tow carriage was placedust the gond of the tank, and the
iceberg model, along with the mounting frame was lowered to align with the holes in the mounting frame and bolted rigidly. The bottom of the iceberg model was generally about 300 mm from the tank floor so that the rigid floor of the scouring tank did not influence the results obtained.

All the instruments were turned on 30 minutes before each test to allow a warm up period. The caps of the piezo-electric sensors were removed, cleaned with cotton swabs, dipped in Tuner Degreaser and recapped each time they were mounted through the brass holder, on the iceberg model. Great care was taken in connecting the microdot connectors to the pressure transducer and amplifier as the slightest amount. of dirt of humidity near the connection or a twist in the connector produced a drifting output voltage. The outputs from the charge amplifiers were fed to the precalibrated input plugs of the tape recorder. The variable D.C. power supply unit which applied a potential difference of 3.0 volts at the ends of the steel wire, along the length of the tank was calibrated each time, using a multimeter. The reference line voltage was connected to one of the input channels of the tape recorder. A typical experiment should measure eightparameters, two load cells, five pressure transducers, and the carriage reference voltage. / When all the instruments were ready to operate, the tow carplage was moved in small incremental, distances such that the bottom of the iceberg

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model just touched the aloping sand bad. At this stage, the carriage reference woltage, the position of the sliver on the meter tape, and the initial footage of the tape recorder were observed and recorded. All the instruments were burned on 30 min, before starting the test, the readings were recorded as the scouting continued, and until the model reached the limit switch. At the end of the scout, the counter reading on the tape recorder, carriage reference voltage, and the reading on the meter tape at the carriage slider were poted. Recorded observations from each channel, together with carriage reference voltage were plotted on 300 x 200 mm paper using a two pen X* plotter.

4.4.3 Post Scour Observations-

In order to check the repeatability of the chaute, each parameter was measured at least five times under similar conditions or until reasonably consistent values (s108) were obtained. In general, there was a very good consistency in the total (one measured for all the models whereas several repetitions were needed for pressure measurements indicating the variation of local densities integrated to be neglegible. In order thankow the uniformity and consistency of the soli density in all peets, a hand penetrometer was used to measure the resistance offered by the soli at several locations on the sand bed. Penetrometer teadings were taken at 1 m intervals both inside and outside the scour track up. to a depth of 400 mm. In some experiments, the sour track formed by the model was manufact the measured dimensions included base width of the sour (5.), top width of the sour (T_{a}) , the inside depth (D_{a}) , and sloping lengths (T_{a}, \circ_{a}) of the source traces sections.

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In addition to the above observations, for purposes of theoretical algulations, it was necessary to measure the surcharge dimensions in front and at the sides of the modal as the scouring proceeded. By this purpose, engrate experiments were conducted for each modal, in which the tow carriage was stopped at intermittant points, and measurements were made. This procedure was also used successfully by cheen (1984). A typical scour track and surpharge dimensions are shown in Fig. 33.

The results of the experiments' and the analysis are discussed in the next chapter.



(GREEN 1984)

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CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

.5.1 . General

This chapter is organized into three major sections. The first part is a discussion of the scour dimensions and shape. In the second part, the types of the streaments conducted are described and a correlation is made between the force required to publy various models into the sloping sand bed and the corresponding pressure distribution on the front face. In the last part, the experimental results are compared with appropriate theoretical methods. Finally, an attempt is made to normalize the scour computations for various keel shapes with reference to the idealized model.

The limitations of modeling iseberg scours in the laboratory and the scope of such models were discussed earlier. The experimental work is limited to verifying the "soil-iceberg interaction." Aspects of the problem such as the effect of velocity on the soil resistance and the model size have been studied and discussed by Green (1984). In the experimental part of this investigation, it was decided to investigate the effect of the keel shape on the resistance of the iceberg to ploughing and take this into account in the theoretical model." After proparing the soil test hed as described in the previous chapter, the iceberg model was positioned, the instruments connected, and the model was towed at a speed of 95 mm/sec. The total soil resistance was measured by the two load cells. A typical force record is shown in Fig. 34. The output from the two load cells was manually added to obtain the total soil reminiance. It may be seen that the load cell records, are similar to those reported by Siemons (1963), chart (1975), and Green (1984) in which the development of successive failure planes (Fig. 35) is depicted by the saw tooth pattern of the record. A similar phenomenon was observed in the load cell records of all iceberg models.

5.2 Scour Profiles and Surcharge Dimensions

In the analytical discussed in Chapter III, the iceberg shape was idealised as a rectangular prismatic shape. The surcharge in front of the iceberg was calculated on the assumption that the volume of the soll scooped out by the iceberg is equal to the sum of the volumes of the soll piled up on the sides and in front of the iceberg. In the attempts to compute the front face soil resistance Chari (1975) measured the surcharge height at the end of scour and assumed a linear variation of it along the length of scour. Green (1984) used different techniques to measure surcharge

dimensions and concluded that stopping the iceberg model at intermediate points along the length of scour did not affect the scour dimensions. Experiments were conducted exclusively to determine the scour dimensions without measuring the loads or pressures. The iceberg model was stopped at several intermediate points and the surcharge was measured at these points and a profile of the surcharge was obtained. The same technique was followed in this investigation. In addition fo the front surcharge/dimensions, the dimensions of the soil on the sides of the iceberg model were also measured to compute the side friction.

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The scour profile at the back of the losberg model was also measured at the end of the test for each model. From the measurements of scour profiles for each model, it was found that irrespective of the front shape of the icebarg, the form of the scour profile was faxatly same. However, depending on the total length of the model, the scour profile at the back of the model was different. From the measured surcharge dimensions, the total volume of the soil in front (V_g) of the iceberg was calculated. These volumes for the different models are shown in Fig. 36. In addition to this, the volume of the soil on the sides of the iceberg model (V_g) , and the volume of the soil on the sides of the scour true, (inclusive of the infilled soil) (V_g) ware calculated.







5.3 Soil-Model Friction

The total soil resistance on the loeberg is the surger of the front face resistance, frictional resistance on the sides and the base friction. In the theoretical model, it was suggested (Chari 1980) that the frictional component of the total resistance may be neglected because of the presence of a thin film of mail water around the loeberg. However, this is not true in the laboratory experiments. Therefore, it is necessary to identify and, evaluate the frictional resistance on the sides and base of the model. From a knowledge of the total resistance and the frictional resistance, the force on the front face alone can be obtained and correlated with the pressure measurements.

As mentioned earlier, iceberg models of different keel shapes were pushed horizontally into the sloping and bed. Theoretically, there should be no base reaction nor base friction since the model moves into a trench pre-out to its width by the advancing front face. However, because of the development of the frontal surcharge, a situation occurs somewhat similar to the bearing capacity of shallow footing, creating a reaction between the soil and the front end of the base. Base pressure and friction was measured in sarilar investigations by Chari (1975), Green (1964), and Abdelhour et al (1980). Attempts were made earlier (Chari, 1975 and green 1944 to evaluate the frictional component by measuring

the pressure distribution on the sides and the base of the iceberg model. The resistance due to friction was obtained by multiplying the averaged pressure, area of contact, and the coefficient of friction. Abelnour and Lapp (1960) directly-measured the load acting on the sides and base along with the total soil resistance. Charl (1975) reported that the pressures on the sides and base did not contribute significant resistance to forward motion of the model for tests in the underconsolidayed clays. For similar studies in dry sand, Green (1984) reported the frictional resistance of the base and sides, as a percentage of total load, to be of the order of 108 and 5% respectively.

In this investigation, a different approach was adopted for estimating the base friction. Two series of tests were bonducted, one by towing the lockery model as it was and another with a thin strip wolded to the front bottom agge of the rectangular primatic model thus eliminating any contact between the base and the soil. The difference between the two tests would thus give the resistance due to base friction. The results obtained by this method are more direct and accurate than these obtained from the method of messuring the pressures. This is confirmed by the fact that in a series of test respections, the measured pressures. For the tests with different frontal keel shapes (models M2)



M3, and M4), bottom friction was eliminated by atfaching the Keels with a slight protrumion below the base level. For the Curved and wedge shaped models (M5 and M45), two series of Eests were conducted, with and without a thin strip wilded to the leading bottom edge.

The residence due to side friction was calculated from measured surcharge dimensions and the active earth pressure coefficient as suggested by Charleand Green (1981).

By subtracting the sum of Daks friction and side friction from the total resistance measured by the load cells, the soil resistance acting on the front face alone was determined and these results will be discussed later.

5.4 Pressure Distribution on the Front, Face.

The soil registance on the front face of the model was also obtained by measuring the pressure distribution using flush-mounted pressure transducers. These front face forces were also subsequently correlated with the various theories of pagsive earth pressure. The typical output of the pressure transducer during a test is show in Fig. 37. The locations of pressure transducers on the front face of the models are indicated in Figs. 39 and 39. Fig. 40 shows the pressure distribution on the front face of the rectangular prismatic model (ML) at scour lengths of 2. 4, 6, and 8 m. Pressures on the front face were measured in both







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series of tests, with the base in contact with the soil and with base friction excluded. . The total force on the front face, was obtained by integrating the pressure, which was then compared with the total soil resistance measured by load cell as shown in Fig: 41. The integrated pressures represents the total force acting only on the front face of the model. The total measured resistance comprises of the front face passive resistance, the frictional force on the sides, and the base friction. The frictional force on sides can be computed from the measured surcharge of the excavated soil, using the active earth pressure coefficients and the coefficient of friction between the model and sand. The computed frictional force was found to be in the order of 4% of the measured. total resistance. ' This compares well with the side friction' of 5% reported by Green (1984). The base friction obtained from the two series of tests ranges from 36% of the total resistance at the beginning of the scour to about 20% at the end of scour. This is slightly higher than that reported by Green (1984). By deducting the sum of base friction and side friction from the total resistance, the force on the front face alone is obtained and compared with integrated pressures in Fig. 41. There is a good correlation between the two types of computation and the small difference between the two, curves is attributed to the variation in pressure readings: and the limited number of pressure transducers used on the front face.

Figure 42 shows the pressure distribution on the front face of the model M2 which has a 30° inclination. The horizontal component of the front face normal force face was obtained from the measured pressures, the total resistance measured by load cell, and the computed side friction are shown in Fig. 43. It may be noted that the base friction was not computed as the lower edge of the front keel was located slightly lower than the base of the model. The normal force on the front face was obtained from the measured pressures. However, the magnitude of the horizontal component of this force depends on the wall friction mobilized between the model and the soil. Figure '43 shows the horizontal component of the normal force for two values of :6, , 6/2 and 26/3; where 5 is the mobilized friction and a the angle of shear resistance of the soil. There is a good correlation between pressure measurements and front face resistance. A similar comparison is shown in Figs 44 and 45 for the model M3, which has a front face inclination of 60°. It has to be noted that the angle of shear resistance & is not constant as is commonly assumed. There is likely to be slight increase in the value of a with increasing depth of cut of the scourtrench. Thus the value of δ_{m} is also not constant and the effect of the variation of δ_m is seen in the correlations in Fig. 45. A comparison of pressure distribution on the front





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face for models M1, M2, and M3 (Figs. 40, 42, and 44) indicates that the front face pressures may be approximated as a hydrostatic distribution even for the inclined surfaces. Also, it can be seen that the measured pressures increase with the inclination of the front face. This is to be expected because when the inclined surface is given a lateral displacement, the displacement normal to the face has two components one vertical and other horizontal. The vertical subgrade reaction is higher than the horizontal subgrade reaction and therefore the pressure increases with increased inclination of the front face. Further, for the same vertical depth of cut, the area of contact between soil and model increases with increasing inclination. The front face pressure distribution on model M4 with a curved keel is shown in Fig. 46. For this model the pressures were also measured normal to the surface. While the pressure distribution was linear for the plane surfaces of models M1, M2, and M3, for the curved model M4, the pressure distribution is non-linear. This is consistent with the earlier observation that the soil pressure not only increases, with depth, but is also influenced by the inclination of the keel, which for the curved surface increases gradually with the depth. The pressure at the leading edge (Fig. 46) was assumed to be zero. However, as discussed earlier, there is likely to be some upward pressure at this edge and ideally, it would have.

been desirable to measure its magnitude. In fact, Chari (1975) and Green (1984) measured it for the rectangular model. in clay and sand respectively. Assuming the distribution shown in Fig. 46, the horizontal component of the force on the front face was computed for the maximum mobilized wall friction and compared with the measured total soil resistance as shown in Fig. 47. There is a relatively large difference (20%) between the integrated pressures and the resistance obtained from load cell measurements. This is in accordance with the foregoing discussion about the pressure between the. leading edge of the model and the first point of pressure measurement. Back calculations were made from the comparison made in Fig. 47 and the most likely pressure distribution on the bottom section of the keel is also shown in Fig. 46. This is realistic and in conformity with the earlier reports of Chari (1975) and Green (1984). The problem of earth pressures on curved surfaces such as the model M4 is not well documented in the geotechnical literature. This is an area of potential further theoretical and experimental research.

The pressure distribution on the model MS which is cylindrical in plan is shown in Fig. 48. This model is semewhat dimilar to a cylindrical pile. The variation of pressure at four scour lengths (2, 4, 6, and 8 m) for the four rows of pressure transducers is shown in the figure.













The pressure is a maximum at the apex of the cylinder and gradually reduces towards the ends of the diameter. Figure 49 shows the pressure distribution in the two reference directions, parallel and normal to the direction of novement of the model. The pressure distribution is somewhat similar to that reported for laterally loaded short piles (Joc 1985). The total force on the model accomputed from the measured pressures and compared with the Dad cell readings as was done for the other models. The results are shown in Fig. 50.

Tests were conducted with the wedge shaped model (M6), but the pressures on the front wedge could not be obtained with consistency due to instrumentation problems. However, the total force on the model, the base friction and side friction are shown in Fig. 51. It can be usen from this figure that base friction was tather high in the initial portion of the scour length because of the wedge shape and the relatively large base area in contact with the soil during the initial portion of the test.

The sverage unit base friction was calculated for the different models and was found to be 2.9, 2.4 and 2.8 kPa for the models MJ. M5, and M6 respectively, which indicates some uniformity.

5.5 Correlation with Theoretical Methods

In the previous sections, the iceberg-soil interaction was verified experimentally, Before incorporating the shape effects in the analytical model, it was first decided to correlate the measured pressures with the available theories of passive earth pressure. Conventional earth pressure theories consider plane surfaces and limited soil deformations such as those occuring in foundations and earth retaining structures. However, some of the recent research on agricultural tillage equipment and earth moving machines has some similarities, with feeberg scouring. The results of Harrison (1973) are supported by experiments. But the surcharge is not large nor is the soil on a clope in tillage experiments. Thus, any theoretical correlation of the iceberg scour experiments require further modifications of existing theories.

The dimensional analysis used in agricultural engineering research, even though simple, is not used here because the variables such as unit weight, internal soil friction and wall friction angle were not changed in this investigation. All the theories currently available and used in the present ahalysis are applicable to plane strain conditions. A review of these was given in Chapter II.

The results for the idealized prismatic model with the vertical front are shown in Fig. 52. The figure also shows the theoretical results using the various theories discussed in Chapter II. All theories give somewhat similar results but the Coulomb's theory is closest to the experimental results. Coulomb's method with a plane failure surface is generally known to overestimate the passive resistance when the wall friction is high; this effect is seen in, the initial portion of the tests. However, the agreement is better in the later part of the experiments when the soil surcharge is greater than the weight of the failure soil wedge. The results from the other theories are within 20% of the experimental values. A similar comparison for models M2 and M3 is shown in Fig. 53 and 54. It can be seen that for the models with a sloping keel, the results are in the general range of values obtained by various theories and no particular theory can be said to be in good agreement with the experimental results.

For the curved profile of model M4, the mearest theory which can be used for the analysis is that of Harrison (1973). For this model, the slope of the contact surface changes with increasing depth of scour. Terzaghi and Pock (1967) and Shields and Tolunay (1973) assume that the angle of wall friction is fully mobilized hid passive sarth resistance generally acts, in the direction suggested by




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Terzaghi (1943). For large inclinations of the wall, if such an assumption is made, the horizontal component of the force will be in the direction of the wall movement; a condition which will not occur. On the other hand, the method of Harrison (1973) facilitates the calculation of the mobilized friction angle from the wall geometry and soil parameters which are then used in computing the soil resistance. However, even in this case, for large inclinations of the front face, this computed friction angle turns out to be negative and underestimates the passive resistance. In fact, a comparison of Harrison's (1973) own experimental results with his predictions were 28% higher. A similar trend is seen with the results obtained from this investigation. As already mentioned, there is a present need to develop a suitable theory of earth pressure for walls of large inclinations and curved profiles.

The theoretical expression for passive resistance on the cylindrical model (M5) was derived using the approach of Prater (1976) in Which the pressure on mine shaft linings has been examined. The results of horizontal force can be given as:

 $P_{h} = \frac{\pi \gamma D^{3}}{\sin (\alpha - \beta)} \quad \frac{\tan (\alpha + \phi) \cos \alpha \cos \beta}{6 \sin (\alpha - \beta)} + \frac{r_{o} \tan (\alpha + \phi)}{2H}$

 $-\frac{k_{0}}{6}\left(1-\frac{\cos\alpha\,\sin\beta}{\sin(\alpha-\beta)}\right)\frac{\cos(\alpha+\phi)\cos\delta}{\cos(\alpha+\phi+\delta)}$ [14]

ere γ = unit weight of sand

= depth of cut

= failure surface inclination to horizontal

= slope angle of backfill

= internal friction of sbil

g. = wall friction

r = radius of cylinder

For the wedge shaped model (M6), passive estimpressures developed on both faces of the wedge were computed and the horizontal component in the direction of travel of the model was calculated using Coulomb's method. There is a good correlation between measured and computed values as shown in/rig. 57.

5.6 Application of Experimental Results to the Scour Model

Results of laboratory tests with models of different shapes has shown that the soll resistance varies with the keel Shape. Assuming the idealized prismatic model (M1) as the reference, the total forces on the other shapes were normalized as shown in Fig. 58. From this comparison,









it may be seen that the total soil resistance on the models increases with an increase in the inclination of the front keel. For the curved profile (M4), the averaged slope of the contact area gradually decreases with increasing acour depth. This is clearly reflected in the total load on the model. A comparison of the loads on the curved keel (M4) and the 60° keel (M3) shows that the total load on the curved keel gradually becomes equal to that on the 60° keel and finally drops below it. Similar normalized graphs for the force on the front force alone are shown in Fig. 59. The resistance on iceberg keels which are curved in plan (M5) or wedge shaped (M6) is smaller than the force on a vertical surface of the same projected width. In general, real iceberg keels are not likely to have a plane slanted surfacesuch as M2 or M3 nor are they likely to have a convex cylindrical face such as model M5. It is most likely that the contact surface may be a combination of these two. Thus, the use of the idealized shape of the analytical model is not likely to be too much in error, perhaps the estimates of maximum scour depths will be marginally on the conservative . side.

In order to examine the shape sflect further, relative factors were assigned for the frontal Tores on keels of different shapes as obtained from Fig. 59. Using these factors, the normalized sour depths were obtained for

different keel shapes for bargs of various sizes and the results are shown in Fig: 60. For the set of standard parameters considered in Chapter III, the variation of the estimated maximum scour depth ranges from 0.5 to 1.3 times the maximum scour depth calculated for the idealized shape. Thus, under the worst conditions, the shape of the keel is likely to cause a margin of stor of +301 to -508 if the scour depths were computed using Ends. 8 and 9. In reality, Decause of the complexity of the keel shape, this error is likely to be far less.



CHAPTER VI

SUMMARY AND CONCLUSIONS

The results of the research reported in this thesis are part of the ongoing project aimed at understanding the geotechnical aspects of the phenomenon of iceberg scouring. In the earlier analytical model (Chari 1975) it was assumed that the iceberg velocity decreases linearly during the process of scouring. This earlier model has now been examined further, and using a step by step iteration technique, it was found that the iceberg velocity variation during scouring is monlinear. The model (Chari 1979) has now been extended to take into account the monlinear velocity. Further parametric analyses show that under the combination of a set of environmental parameters, the difference in the scour depth computations between the linear and monlinear velocity assumptions could be as much as about 208.

The scour potential of a capsizing and bottom penetrating iceberg was examined and it was found that such icebergs could quue a long scour track by a pockmark on the seafloor, depending on the initial depth of penetration, iceberg size, and the type of the seafloor. Upper and lower bound values were established for such initial penetration for icebergs of a given size.

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Physical models of iceberg scouring are only partial models as they do not simulate the phenomenon in its entirety. Nevertheless, these models are essential in understanding the geotechnical aspects of the iceberg-seabed interaction and as a subsequent feedback into the analytical model. Tests were conducted with models of different keel shapes.

For a rectangular prismatic model, the measured frontal force due to soil pressure is in good agreement with Coulomb's method.

The soll resistance on models with an inclined keel increases with the angle of inclination of the keel. The soll pressure on a curved keel is nonlinear. The total soll resistince on such Keels depends on the average slope of the soll-keel contact surface. There is at present no satisfactory theory for computing the earth pressure on such curved surfaces.

The soil resistance on wedge shaped and cylindrical models is less than that for an equivalent rectangular prismatic model.

Results of tests on physical models of different shapes were fedback into the analytical model and the results were normalized with reference to the idealized prismatic shape. It is concluded that the range of the theoretical shour depths obtained from the idealized model will be

acceptable in normal engineering practice, considering the fact that the keel of a real iceberg is likely to be curved or inclined in two planes if not three.

It is recommended that further experimental and theoretical research should be conducted with curved keel shapes for which there are no solutions at present. Previous investigation has show that (Chari 1975) Green 1984) there is odil movement below that (Chari 1975). Green 1984) there is odil movement below the scour and this effect was examined for the rectangular primetic models. It is recommended that further work be conducted for keels of different shapes so that a proper evaluation may be made of the preseures ohpipelines buried below the potential depth of maximum scour.

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APPENDIX - A

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COMPUTER PROGRAMS

C THIS PROGRAMME COMPUTES THE MAXIMUM DEPTH OF

C SCOUR IN COHESIVE SOILS ACCOUNTING NON-LINEAR

C VELOCITY AND INITIAL DEPTH OF SCOUR

REAL LSTAR,L,LD,LNEW,LDN,V,C,K,K2,SLP,REP,DENS,B,W,KE,A,DRAFT OPEN(UNIT=20,FILE='ICEBRG.ANS',TYPE='NEW')

06 ROW=1.025

OPEN(UNIT=21,FILE='ICEBRG,DAT',TYPE='OLD')

READ(21,*) NDATA

DO 180 I=1,NDATA

READ(21,*) V, DENS, C, SLP, W, B, CD, S, FAC

WRITE(20,*) 'V=',V,' DENS=',DENS,' TAU=',C,' SLP=',SLP,

'W=',W,'B=',B,'CD=',CD,'S=',S

REP=SLP

VCUR=V

GAMA=DENS-10.05

C ANALYSIS IS BEING DONE IN INCREMENTS OF LENGTH

DL=5.0

L=0.0

DLSTOP=0.001

VLIMIT=0.0001

30 K = 1.0/SLP + 1.0/REP

40 KE=W*V*V/(2.0*9.806)

AB3=KE

41 A = 2.644*(3*W/(4*3.14*8.8))**0.67

42.DRAFT = 1.57*(3*W/(4*3.14*8.8))**,33

BLDMT=(CAMA'S*'4'S''8'B/s.0+O'B'5''S+LAT4/3'C'S'*3)*SLP VOLD=VCUR ES=0.0 EP=KE _ADD=0.0 ENET=KE VNEW=VCUR ESCUM=0.0 SMEADD=0.0 LPRINT=J/100 C TYPE*LES.EP_EADD.KE,VNEW,ESCUM,SMEADD L=L+DL D=L/SLP C LD IS NOW OBTAINED BY NEWTON - RAPHSON METHOD

KANAN CANANAN K

· LD=L/10

49 ITER=1

```
60 FDX = 8.0*K*K*LD**3 + 12.0*K*K*L*LD*LD
  2 + 20*LD*(20*K*K*L*L + 8.0*K*L*B/REP)
 70 LDN = LD - FX/FDX
 71 IF(ABS(LD-LDN).LT.0.1) GO TO 74
    ITER=ITER+1
    IFITTER GE 50) GO TO 96
 72 LD = LDN
 73 GO TO 50
 74 LD = LDN
C
    TYPE*.'LD='LD
 75 H = L/SLP + LD/REP + LD/SLP
 76 HD = LD/REP + LD/SLP
    D1=S+L/SLP
    K2=LD*K/(S+L/SLP)
    RESIST=GAMA*(H+S)**2*B/2.0+2.0*C*D1*B+1.414*C*D1*D1
    TLIMIT=(GAMA*(H+S)**2*D1*B/6.0+C*D1*D1*B+
    1.414*C*D1**3/3.0)*SLP
    TLIMIT=TLIMIT*FAC
    LPRINT=L/100
    IF(LPRINT*100.EO.L.OR.L-LAST.GE.100)TYPE* "L=' LLD K2
    LAST=L
    ES=TLIMIT-BLIMIT
    ETEMP=ENET-ES+0.5*CD*ROW*A*(VCUR-VOLD)**2*DL
    VNEW=SORT(ETEMP*2.0*9.806/W)
    IF(VNEW LT.VLIMIT.OR.ENET.LT.50.0)GO TO 96
    VAVSQ=((VNEW-VCUR)**2+(VOLD-VCUR)**2)/2.0
    EADD=CD*ROW*A*VAVSQ/2.0*DL
    ENET=KE-ES+EADD
C.....
                OUTPUT INFORMATION
    IF(ES.GT.ENET)TYPE*, 'FOR L=',L,'ES>ENET=',ENET,'DL=',DL
    IF(ES.GT.ENET)TYPE*,'L=',L,'FDRAG=',EADD/DL,'V=',VNEW,
  1 'RVSQ=',(VCUR-VNEW)**2,'P=',RESIST
    IF(ES.GT.ENET)WRITE(20,*)'L='L.'FDRAG='EADD/DL.'V='.VNEW.
    1 'RVSQ='.(VCUR-VNEW)**2.'P='.RESIST
C
C*****
    IF(ENET.LE.ES) GO TO 90
   ESCUM=ESCUM+ES
    ABI=ESCUM-
    SMEADD=SMEADD+EADD
    AB2=SMEADD
    AB4=AB3/AB1*100
    AB5=AB2/AB1*100
    KE=ENET
```

50 FX = 2.0*K*K*LD**4 + 4.0*K*K*L*LD**3 + LD*LD*(2.0*K*K*L*L 2 + 3.0*K*L*B/REP) - 3.0*L**3*B/REP/SLP-5.0*S*L*L*B/REP LPRINT=L/100 IF(LPRINT*100EQ.L)GO TO 81 IF(DL.GE.L0)GO TO 85 IF(DLLT.10.AND.L-LPASTLT.25) GO TO 85 81 LPAST=L

C TYPE*,L=',L,FDRAG=',EADD/DL,V=',VNEW,P=',RESIST C 84 TYPE*,L,ES,EP,EADD,KE,VNEW,ESCUM,SMEADD WRITE(20,*)L=',L,V=',VNEW,P=',RESIST,'WSOIL=',ESCUM,

1 'FDRAG=',EADD/DL,'EDRAG=',SMEADD,AB3+SMEADD

85 VOLD=VNEW

BLIMT=TLIMIT

90 IF (ENET. LE.ES. AND. DL.LE. DLSTOP)GO TO 96 IF (ENET. GT.ES)GO TO 95

L=L-DL

C

IF(DL.EQ.1.0)GO TO 94

IF(DL.EQ.5.0)DL=1.0

IF(DL.EO.1.0)GO TO 95

94 IF(DL.LT.5.0)DL=DL/10.0

95 L=L+DL

IF(KELE.0.0) GO TO 96 .

IF(KE.GT.0.0)GO TO 49

96 WRITE(20,*)'L=',L,'D=',D1,'V=',VNEW,' ENET=',KE

D=L/SLP

180 CONTINUE STOP

END

C THIS PROGRAMME COMPUTES THE MAXIMUM SCOUR DEPTH

- C FOR COHESIVE FRICTIONAL SOIL TAKING INTO ACCOUNT
- C NONLINEAR VELOCITY

REAL L,L1,KE

COMMON/BLOC1/C,PHID,SLP,B,L,L1,WO,GAMA,H,D,P

OPEN(UNIT=20;FILE='ICEBRG.ANS',TYPE='NEW')

06 ROW=1.025

OPENUMT=11FHE='ICEBRGDAT',TYPE='OLD') READ(21,*) NDATA DO 180 I=1,NDATA READ(21,*) V.DENS (.SLP, W.B.(CD, PHID WRITE(20,*) 'V.=',V', DENS=',DENS,'C.=',C, 'SLP=',SLP, WRITE(20,*) 'V.=',V', DENS=',DENS,'C.=',C, 'SLP=',SLP, 'V.UE=V' CAMA_=DENS.10.05

C ANALYSIS IS BEING DONE IN INCREMENTS OF LENGTH DL=5.0 L=0.0

DLSTOP=0.001 VLIMIT=0.0001

40 KE=W*V*V/(2.0*9.806)

41 A = $2.644^{*}(3^{*}W/(4^{*}3.14^{*}8.8))^{**}0.67$ 42 DRAFT = $1.57^{*}(3^{*}W/(4^{*}3.14^{*}8.8))^{**}.33$

```
POLD=0
   VOLD=VCUR
    ES-00
    EP-KE
   EADD=0.0
   ENET=KE .
    VNEW=VCUR
   ESCUM=0.0
   SMEADD=0.0
   LPRINT=L/100
   TYPE* L.ES.EP.EADD.KE.VNEW.ESCUM.SMEADD
C
   L=L+DL
49 CALL SURCH
   D=L/SLP
   CALL RESIST
```

PNEW=P

LPRINT=L/100 ES=0.5*(PNEW+POLD)*DL ETEMP=ENET-ES+0.5*CD*ROW*A*(VCUR-VOLD)**2*DL VNEW=SORT(ETEMP*2.0*9.806/W) IF(VNEWLT, VLIMIT, OR, ENETLT, 50.0)GO TO 96 VAVSO=((VNEW-VCUR)**2+(VOLD-VCUR)**2)/2.0 EADD=CD*ROW*A*VAVSO/2.0*DL ENET=KE-ES+EADD "OUTPUT INFORMATION IF(Enet.LT.Es)TYPE*, 'FOR L=',L'ES>ENET=',ENET, 'DL=',DL,'L1=',L1 IF(ENET LE ES) GO TO 90 ESCUM=ESCUM+ES SMEADD=SMEADD+EADD KE-ENET LPRINT=L/100 IF(LPRINT*100.EO.L)GO TO 81 IF(DL.GE.1.0)GO TO 85 IF(DL.LT.1.0, AND.L-LPAST.LT.25) GO TO 85 81 LPAST=L TYPE*,'L=',L,'FDRAG=',EADD/DL,'V=',VNEW,'P=',PNEW,'Li=',L1 WRITE(20.*)'L=!L'V='.VNEW.'P='.PNEW.'WSOIL='.ESCUM 1 'FDRAG=',EADD/DL,'EDRAG=',SMEADD,AB3+SMEADD 85 VOLD=VNEW POLD=PNEW IF(ENET.GT.ES)GOTO 95 90 IF(VNEW.LT.VLIMIT. AND. DL.LE.DLSTOP)GOTO 96 IF(ENET.LE.ES AND. DL.LE.DLSTOP)GO TO 95 L=L-DL IF(DL:E0.5.0)DDL=1.0 IF(DL.EO.1.0)DDL=0.1 IF(DL.EO.0.1)DDL=0.01 IF(DL, EQ.0.01)DDL=0.001 DL=DDL

```
95 L=L+DL
```

```
F(KE.GT.0.0)GO TO 49
```

```
C.....
```

```
08 WRITE(9,*)T_1,D=1,D=0,V=',VNEW, ENET=',KE
C_____YTPF*_L=',L_1L=',L,WO=',WO
G_____
G____
Lie OONTHUE
STOP
END
```

- IF(ITTAD.LT.50.0)GO TO 5 TYPE*, 'PMIN=', PMIN, 'AT TITA=', TMIN
- IF(TTTAD.LT.50.0)GO TO 5
- 10 TITAD=TITAD+1.0
- IF(P.GE.PMIN)GOTO 12 IF(P.GT.0.0 AND. P.LE.PMIN)TMIN=TITAD IF(P.GT.0.0 AND. P.LE.PMIN) PMIN=P
- CCA=(H+D)*B*CA P=((WO+W+(S+2.0*SS)*SIN(TITA)+CCA)*SIN(TITA+PH)+(S+2.0*SS)* COS(TITA)*cos(tita+phi))/COS(DELTA+PHI+TITA)

48

- 2 *TAN(PHI)).
- W=GAMA*B*(0.5*D*D*COS(BETA)*COS(TITA)/SIN(TITA-BETA)) S=(B*D*COS(BETA)/SIN(TITA-BETA))*C SS=(0.5*D*D*COS(BETA)*COS(TITA)/SIN(TITA-BETA))* (C+AK0*(GAMA*D/3.0+WO*SIN(TITA-BETA)/(B*D*COS(TITA)))

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1 (L1/COS(ALP)-(H+D)*COS(TITA)/SIN(ALP+TITA))* 2 (L1/COS(BETA)-D*COS(TITA)/SIN(TITA-BETA))

IF(D.EQ.0.0)GOTO 15 AK0=0.0 TITAD=5.0 PMIN=10000000.0 TITA=TITAD*FAC IF(TITA=BETA.EC.0.0)GOTO 10

WO=Q-0.5*GAMA*B*SIN(ALP+BETA)*

SUBROUTINE RESIST REAL LJL COMMON/BLOCI/C,PHID,SLP,BL,LI,WO,GAMA,H,D,P TYPEP'C=',C,PHID,SLP,GAMA,B,D,H,WO,P,L Q=W0 ALPC-0.0 CA=ALFC'C DELTAJ=PHID/8.0 REP=SLP PI=3.1415927 PI=3.1415927 PI=3.1415927 PI=3.1415927 PI=3.1415927 DELTAJ=PETAJ*PAC DELTA-DELTAJ*PAC DETA=DELTAJ*PAC DETA=DELTAJ*PAC DETA=DELTAJ*PAC

COMMON/BLOCI/C.PHID.SLP.B.L.LI.WO.GAMA.H.D.P REP-SLP K=1.0/SLP+1.0/REP L1=L/10.0 DO 10 I=1 50 F=2.0*K*K*L1**4+4.0*K*K*L*L1**3+LT*L1*(2.0*K*K*L*L +3.0*K*L*B/REP}-3.0*L**3*B/REP/SLP 1 FD=8.0*K*K*L1**3 + 12.0*K*K*L*L1*L1 1 +2.0*L1*(2.0*K*K*L*L + 3.0*K*L*B/REP) ALIN=L1-F/FD IF(ABS(ALIN-L1),LT.0.1)GOTO 15 C . TYPE* LIALIN LI=ALIN IFILEO.50) TYPE*, 'ITERATION EXCEEDED'. 10 CONTINUE 15 LI=ALIN H-K+1.1 VOLF=L1*H*B/2.0 TYPE*,'L=',AL,'L1=',AL1,'VOLF='.VOLF C WO=GAMA*VOLF RETURN END

P=PMIN IF(DEQ.0.0)P=0.0 RETURN END

SUBROUTINE SURCH

12

15

65.1

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C THIS IS A GENERALIZED PROGRAMME FOR MODELS
C M1 M2 AND M3 TO COMPUTE FRONT FACE RESISTANCE
C. USING COULOMB'S METHOD. BHO IS FRONT FACE INCLINATION
C ALL VARIABLES ARE SELF EXPLANATORY
    OPEN/UNIT=19.FILE='EXP.DAT'.TYPE='OLD'
    OPEN(UNIT=20.FILE='EXP.ANS'.TYPE='NEW')
    READ(19.*)N
    DO 5.I=1.N
    READ(19.*)AL.VO
    GAMA=17.0
    AK0=0.5 .
    D=AL/35.0
    B=0.5
    WRITE(20.7)AL.VO
    FORMATI2X 'RECTANGULAR PRISMATIC',//,'SCOUR
   LENGTH=',F4.2,5X,'VOL. OF OVERBURDEN='.E8.2)
    PHT=35.5*3.142/180.0
    DELTA=23.0*3.142/180
    BETA=1.637*3.142/180.0
    RHO=0.0*3.142/180.0
C TOTAL WEIGHT = WT. OF VARIABLE WEDGE + WT. OF OVERBURDEN
     WT = WW + WO
    WO=GAMA*VO
    TITAD=5.0
     TITA=TITAD*3.142/180.0
110
    WW=GAMA*B*(0.5*(D*COS(BETA))**2*COS(RHO+TITA)/
   1 COS(RHO+BETA)/ SIN(TITA-BETA))
    WT=WW + WO
     TYPE*,'WW=',WW,'WO=',WO,'WT=',WT
    Q=WO*COS(RHO+BETA)*SIN(TITA-BETA)/B/D/
   1 COS(BHO+TITA)/COS(BETA)
    FS=2.0*(WW/GAMA/B)*(AK0*(Q+GAMA*D/2.0))*TAN(PHI)
    P=(WT*SIN(TITA+PHI)+FS*COS(PHI))/COS(TITA+PHI+DELTA+RHO
    PH=P*COS(RHO+DELTA)
     TYPE*.'Q='.Q.'FS='.FS.'P='.P.'PH='.PH
    WRITE(20.9)TITAD, WO, WW, WT, PH
     FORMAT('FOR TITA=',F4.1,2X,'WO=',E8.2,2X,'WW=',E8.2,
    2X.'WT='.E8.2 .2X.'P='.F9.4)
    TITAD=TITAD+1.0
    IF(TTTAD.LE.30)GO TO 10
     CONTINUE
    STOP
    END
```

C THIS PROGRAMME COMPUTES THE FRONTFACE RESISTANCE C FOR MODELS M1, M2 AND M3 USING LOGARITHMIC SPIRAL C METHOD AND REFERRED TO AS TERZAGHI AND PECK METHOD.

OPEN(UNIT=20.FILE='EXP.DAT'.TYPE='OLD') OPEN(UNIT=21.FILE='EXP.ANS'.TYPE='NEW') OPEN(UNIT=22.FILE='WASTE.ANS'.TYPE='NEW') ALPHAD=90.0 PHID-35 5 GAMA=17.0 B=0.5 BETA=ATAN(1.0/35.0) PI=3.1415927 FAC=PI/180.0 ALP1=26.66*FAC ALP2=27.84*FAG ALPHA=ALPHAD*FAC PHI=PHID*FAC READ(20,*)N DO 10 1=1 N READ(20.*)AL.VO WO=VO*GAMA D=AL/35.0 DO 10 J=1.116 TITAD=J-26 TITA-TITAD*FAC AB=D/SIN(ALPHA) ETA=PHI-TITA ANGOAB=ALPHA-(TITA+PI/2.0-PHI) ANGOBA=(PI-ALPHA)+(ALP1-BETA) TITAM=PI-ANGOAB-ANGOBA delta=23.0*fac DELTAD=DELTA/FAC ALP3=PI-ALPi-(PI/4.0+PHI/2.0) ALP4=BETA+ALP3-PI/2.0 ALP5=ALPHA-PI/2.0+DELTA AO=AB*SIN(ANGOBA)/SIN(TITAM) R0=AO CO=R0*EXP(TITAM*TAN(PHI)) BO=AB*SIN(ANGOAB)/SIN(TITAM) BC=CO-BO BD=BC*SIN(PI/4.0+PHI/2.0)/SIN(ALP3) CD=BC*SIN(ALP1)/SIN(ALP3) CE=CD*SIN(ALP3)/SIN(ALP2) DE=CD*SIN(PI/4.0+PHI/2.0)/SIN(ALP2)

Ser Sording.

-SIN(ALP5)*(XH-XO)) PQ=(AMFQ+Q*BD*((XB+XD)/2.0-XO))/(COS(ALP5)*(YO-YI)

Q=W0(/B*(BD+DE)) FQ=Q*TAN[F1.4s+FH[/20]***CD AMABO=AABO*GAMA*(XABO-XO) AMACBO=AACBO*GAMA*(XABO-XO) AMBCB=AFCCGO*GAM*(XACBO-XO) AMBCB=ABCO*GAMA*(XBCD-XO) AMBCB=P0*COS(ALP4)*(YC-YT)+FC*SIN(ALP4)*(XF-XO) AMFG=B0*COS(ALP4)*(YC-YT)+FC*SIN(ALP4)*(XG-XO) AMFG=B0*COS(ALP4)*(YC-MH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-MH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH) COS(ALP4)*(YC-YH)+COS(ALP3)*(YC-YH)+COS(ALP3)*(YC-YH)+COS(ALP4)*(YC-YH)+COS(ALP3)*

 $\begin{array}{l} AABO = & (XA^*YB - XB^*YA + XB^*YO - XO^*YB + XO^*YA - XA^*YO)^{0.5} \\ ABCD = & 0.5^*(XB^*YC - YB^*XC + XC^*YD - YC^*XD + XD^*YB - YD^*XB) \\ AACBO = & RO^{+2}/4.0/TAN(PHI)^{0}(EXP(2.0^{+}TTAA^{+}TAN(PHI)) - 1) \\ FG = & 0.5^*(AMA^*CD^{+2}TAN(PI/4.0 + PHI/2.0)^{+2}) \end{array}$

XACBO=XO+CGACBO

XA=0.0 YA=0.0 XB=D*SIN(ALPHA-PI/2.0)/SIN(ALPHA) YB-D XO=XA-AO*SIN(ETA) YO=YA+AO*COS(ETA) XC=XB+BC*COS(ALP1-BETA) YC=YB-BC*SIN(ALP1-BETA) XD=XB+BD*COS(BETA) YD=YB+BD*SIN(BETA) XE=XD+DE*COS(BETA) YE=YD+DE*SIN(BETA) XF=XC+(XD-XC)/3.0 YFYC+(YD-YC)/3.0 XG=XC+(XD-XC)/2.0 YG=YC+(YD-YC)/2.0 XH=XA+(XB-XA)/3.0 YH=YA+(YB-YA)/3.0 XI=XA+(XB-XA)/2.0 YI=YA+(YB-YA)/2.0 XABO = (XA + XB + XO)/3.0YABO=(YA+YB+YO)/3.0 XBCD=(XB+XC+XD)/3.0 YBCD = (YB + YC + YD)/3.0CGACBO=4.0*R0*TAN(PHI)/3.0/(EXP(2.0*TITAM*TAN(PHI))-1) *(3.0*TAN(PHI)*SIN(TITAM+ETA)*EXP(3.0*TITAM*TAN(PHI)) 2 -COS(TITAM+ETA)*EXP(3.0*TITAM*TAN(PHI))-3.0*TAN(PHI)* SIN(ETA)+COS(ETA))/(1.0+9.0*TAN(PHI)**2)

-SIN(ALP5)*(XI-XO)) P=PG+PQ 1

C

PH=P*COS(ALP5) PH=0.5*PH WRITE(21,*)AL, TITAD, DELTAD, PH TYPE*, AL, TITAD, DELTAD, PH 10 CONTINUE STOP END

C THIS PROGRAMME IS USED TO COMPUTE FRONT FACE RESISTANCE C OF MODELS MI, M2 AND M3 WITH SLOPING BACKFILL AND C SURCHARGE USING HARRISON'S METHOD.

SURCHARGE USING HARRISON'S METHOD.

C FOR NOTATION, PLEASE REFER TO TEXT.

OPEN(UNIT=20,FILE='EXP.DAT',TYPE='OLD') OPEN(UNIT=21,FILE='EXP.ANS',TYPE='NEW')

PHID=35.5 ALPHAD=150.0 ALP1D=26.66 ALP2D=27.84 GAMA=17.0 B=0.5 BETA=ATAN(1.0/35.0) WRITE(21,5)ALPHAD WRITE(21,6) FORMAT(/,5X,'INCLINED PROFILE',F5.1./) FORMATISX.'L.XO.YO.XC.YC.XD.YD.XE.YE.TITA.DELTA.PH'./) PI=3.1415927 FAC=PI/180.0 PHI-PHID*FAC ALPHA=ALPHAD*FAC ALP1=ALP1D*FAC ALP2=ALP2D*FAC READ(20.*)N DO 10 I=1.N READ(20.*)AL.VO D=AL/35.0 . WO=VO*GAMA

ETA=PHI

TITAM=PI/2.0-PHI-ALP1+BETA ALP3=PI-ALP1-(PI/4.0+PHI/2.0) ALPG=BETA+ALP3-PI/2.0 ALPH=ALPG

BC=D/COS(I[#]HI) R0=BC BD=R0*EXP(TITAM*TAN(PHI)) BE=SIN(PI/4.0+PHI/2.0)*BD/SIN(ALP3) DE=SIN(PI/4.0+PHI/2.0)*DE/SIN(ALP3) EF=SIN(PI/4.0+PHI/2.0)*DE/SIN(ALP3)

PPG=(AMBDE+AMBCD+AMFC)/(20/30°BC PPQ=(AMFC+Q*BE*(XE-XB)/2.0)/(1.0/2.0*BC PP=PPG+PPQ TITA=(270-2.0*ALPHAD-PHID)*FAC TITAD=TITA/FAC

$$\begin{split} ABDE=&ABS(0.5^{4}(XB^{4}YD-XD^{4}YB+XD^{4}YE-XE^{4}YD-XE^{4}YB-XB^{4}YE)),\\ ABCD=&ABS(R0^{*+2}/(4.0^{4}TAN(PHI))^{*}(EXP(2.0^{4}TITAM^{4}TAN(PHI)-1))),\\ AABC=&ABS(0.5^{4}(XA^{4}YB-YA^{4}XB+XB^{4}YC-YB^{4}XC+XC^{4}YA-YC^{4}XA)). \end{split}$$

XBCD=CGBCD+XB

Q=WO/(B*(BE+EF)) FQ=Q*TAN(PI/4.0+PHI/2.0)**2*DE

3 SIN(ETA)+COS(ETA))/(1.0+9.0*TAN(PHI)**2)

FG=0.5*GAMA*DE**2*TAN(PI/4.0+FHI/2.0)**2

CGBCD=4.0*R0*TAN(PHI)/3.0/(EXP(2.0*TITAM*TAN(PHI)-i) 1 *(3.0*TAN(PHI)*SIN(TITAM+ETA)*EXP(3.0*TITAM*TAN(PHI)) 2 -COS(TITAM+ETA)*EXP(3.0*TITAM*TAN(PHI))-3.0*TAN(PHI)*

 $\begin{array}{l} YB{=}D.\\ XC{=}XB{+}BC^*SIN(PHI)\\ YC{=}0.\\ XD{=}XB{+}BD^*COS(ALPI+BETA)\\ YD{=}YB{+}BD^*SIN(ALPI+BETA)\\ YD{=}YB{+}BE^*SIN(BETA)\\ YE{=}YB{+}BE^*SIN(BETA)\\ YE{=}YB{+}BE^*SIN(BETA)\\ XG{=}XD{+}(XE{-}XD)^*LO^{3,0}\\ XG{=}XD{+}(XE{-}XD)^*LO^{3,0}\\ XH{=}_XD{+}(XE{-}XD)^*LO^{3,0}\\ XH{=}_XD{+}(XE{-}XD)^*LO^{3,0}\\ YH{=}YD^+(XE{-}XD)^*LO^{3,0}\\ YH{=}YD^+(XE{-}XD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*LO^{3,0}\\ YH{=}YD^+(YE{-}YD)^*U^{3,0}\\ YH{=}YD^+(YE{-}YD^+(YE{-}YD)^*U^{3,0}\\ YH{=}YD^+(YE{-}YD^+(YE{-}YD)^*U^{3,0}\\ YH{=}YD^+(YE{-}YD^+(YE{-}YD)^*U^{3,0}\\ YH{=}YD^+(YE{-}YD^+$

XBDE = (XB + XD + XE)/3.0

XB-D*SIN(ALPHA-PI/2.0)/SIN(ALPHA)

BF=BE+EF XA=0.0⁴ YA=0.0



C. 00 137-104

C THIS PROGRAMME IS SET TO COMPUTE FRONT FACE RESISTANCE OF C CURVED PROFILE (M4) USING THE PRINCIPLE OF HARRISON (1973). C THE CURVED PROFILE IS APPROXIMATED AS INCLIMED FLANE C SURFACE HAVING THE AVERAGE INCLIMATION OF CONTACT C SURFACE.

OPEN(UNIT=20,FILE='EXP.DAT',TYPE='OLD') OPEN(UNIT=21,FILE='EXP.ANS',TYPE='NEW')

PHID=35.5 ALPID=26 66 AL POD-97 84 GAMA=17.0 B-05 BETA=ATAN(1.0/35.0) WRITE(21.5) C WRITE(21.6) 5 FORMAT(/.5X.'CURVED PROFILE'.F5.1./) FORMAT(5X, L, XO, YO, XC, YC, XD, YD, XE, YE, TITA.DELTA.PH'./) 6 PI=3.1415927 FAC=PI/180.0 PHI=PHID*FAC ALPI=ALPID*FAC ALP2=ALP2D*FAC READ(20,*)N DO 10 I=1.N C THE POINT OF APPLICATION OF RESISTANCE. COMPUTED FROM C MEASURED PRESSURE DISTRIBUTION IS SUPPLIED (GGF) READ(20,*)AL,VO.CGF D=AL/35.0 WO=VO*GAMA XB=SORT(0.09-(0.3-D)**2) YB=D ALPHA=PI-ATAN(YB/XB) ALPHAD=ALPHA/FAC OMEGA=ATAN(XB/(0.3-D)) OMEGAD=OMEGA/FAC ETA=PHI TITAM=PI/2.0-PHI-ALP1+BETA ALP3=PI-ALP1-(PI/4.0+PHI/2.0)

ALPG=BETA+ALP3-PI/2.0
FG=0.5*GAMA*DE**2*TAN(PI/4.0+PHI/2.0)**3 Q=WO/(B*(BE+EF)) FQ=Q*TAN(PI/4.0+PHI/2.0)**2*DE

1 TAN(PHII)-1)) AABC=ABS(0.5*()A*YB-YA*XB+XB*YCYB*XC+XC*YA-YC*XA)) COFAR==OMEGA*0.009/2.0.0.5*0.00*SIN(OMEGA) AABC=AABC-COFAR

ABDE=ABS(0.5*(XB*YD*XD*YB+XD*YE-XE*YD+XE*YB-XB*YE)) ABCD=ABS(R0**2/(4.0*TAN(PHI))*(EXP(2.0*TITAM*

XBCD=CGBCD+XB

3 3.0*TAN(PHI)* SIN(ETA)+COS(ETA))/(1.0+9.0*TAN(PHI)**2)

2. -COS(TITAM+ETA)*EXP(3.0*TITAM*TAN(PHI))-

XBDE=(XB+XD+XE)/3.0 CGBCD=4.0*R0*TAN(PHI)/3.0/(EXP(2.0*TITAM*TAN(PHI))-1) 1 *(3.0*TAN(PHI)*SIN(TITAM+ETA*EXP(3.0*TITAM*TAN(PHI))

C. C. S. A. S. S. S. S. S. S.

EF=SIN(PI/4.04 BF=BE+EFA

XA=0.0

 $\begin{array}{l} BC = D/COS(PHI)\\ R0 = BC\\ BD = R0^+EXP(TITAM^+TAN(PHI))\\ BE = SIN(PI/4.0+PHI/2.0)^+BD/SIN(ALP3)\\ DE = SIN(ALP1)^+BD/SIN(ALP3)\\ EF = SIN(PI/4.0+PHI/2.0)^+DE/SIN(ALP3)\\ \end{array}$

ALPH=ALPG

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AMBDE=ABDE*GAMA*(XBDE-XB) AMBCD=ABCD*GAMA*(XBCD,XB) AMFG=FG*COS(ALPG)*(YB-YG)+FG*SIN(ALPG)*(XG-XB) AMFQ=FQ*COS(ALPH)*(YB-YH)+FQ*SIN(ALPH)*(XH-XB) PPG=(AMBDE+AMBCD+AMFG)/(2.0/3.0*BC*COS(PHI)) PPO=(AMFO+Q*BE*(XE-XB)/2.0)/(1.0/2.0*BC*COS(PHI)) PP=PPG+PPO ALPHAD=180.0-OMEGAD*CGH ALPHA=PI-OMEGA*CGF TITA=(270-2.0*ALPHAD-PHID)*FAC TITAD=TITA/FAC DELTA=ATAN(SIN(TITA)*SIN(PHI)/(1.0+COS(TITA)*SIN(PHI))) F(DELTA/FAC.GT.23.0) DELTA=23.0*FAC IF(DELTA/FAC.LT.-23.0) DELTA=-23.0*FAC DELTAD=DELTA/FAC P=COS(PHI)*(PP+AABC*GAMA*TAN(PHI))/COS(ALPHA-PI/2.0+DELTA+PHI) PH=P*COS(ALPHA-PI/2.0+DELTA) PH=PH*B WRITE(21.7)D.XO.YO.XC.YC.XD.YD.XE.YE.TITAD.PHID.DELTAD.PH FORMAT(2X,F4.2.8(2X,F6.2),2X,F6.2.2X,F6.2.2X,F6.2,F8.4) TYPE* AL, ALPHAD, DELTAD. 'PH='.PH WRITE(21.8)AL ALPHAD DELTAD PH FORMATI2X 'L=' F4.1.2X 'EOUTVALENT ALPHA=' F7.2.2X 1 'DELTA='.F6.2.2X.'PH='.F8.3) C 'TYPE*,'ALPHA=',ALPHAD,'TITA=',TITAD,'ETA=',ETA/FAC ' TYPE*,'TITAM=',TITAM/FAC,'ALP3=',ALP3 TYPE*.'ALPG=',ALPG/FAC,'ALPH=',ALPH/FAC TYPE*.'BC='.BC,'BD=',BD,'BE=',BE,'DE=',DE,'EF=',EF,'BF=',BF C TYPE*.'XB='.XB.'YB='.YB C TYPE*.'XC='.XC.'YC='.YC C TYPE*,'XD=',XD,'YD=',YD C TYPE*,'XE=',XE,'YE=',YE TYPE* 'XF='.XF.'YF='.YF C TYPE*,'XG=',XG,'YG=',YG C TYPE*.'XH='.XH.'YH='.YH C. TYPE*,'AABC=',AABC,'ABCD=',ABCD,'ABDE=',ABDE' C TYPE*.'FG='.FG.'FQ='.FQ TYPE*, 'WABC=', AABC*GAMA, 'WBCD=', ABCD*GAMA, 'WBDE=', GAMA C TYPE*,'AMBCD=',AMBCD,'AMBDE=',AMBDE,AMFG,AMFQ IF(DELTAD.LT.-24.0 OR. DELTAD.GT.24) TYPE*.'NO VALUE"



C THIS PROGRAMME CALCULATES FORCE ON THE C CYLINDRICAL MODEL. COULOMB'S METHOD IS USED C ON SIMILAR LINES SUGGESTED BY C PRATER. SLOPE OF BED AND SURCHARGE ARE CONSIDERED.

OPEN(UNIT=20.FILE='EXP.DAT'.TYPE='OLD') OPEN(UNIT=21.FILE='EXP.ANS'.TYPE='NEW') OPEN(UNIT=22.FILE='EFFORT.ANS'.TYPE='NEW') PHID=35.5 DELTAD=23.0 BETA=0.0 GAMA=17.0 PIS-3 1415927 FAC=PI/180.0 PHI-PHID*FAC DELTA=DELTAD*FAC READ(20.*)N DO 10 1=1.N READ(20.*)AL.VO WO=VO*GAMA PMIN=1000 D=(AL-0.125)/35.0 ALPHAD=5 . DO 20 J=1.30 ALPHA=ALPHAD*FAC TRM1=COS(ALPHA)*COS(BETA)/SIN(ALPHA-BETA) W1=PI*GAMA*(D**3/6.0*TRM1**2+D*D*0.25/2.0*TRM1) WT=WO+W1 AK0=1.0-SIN(PHI) TRM2=COS(ALPHA)*SIN(BETA)/SIN(ALPHA-BETA) T=AK0*GAMA*D**3/6.0*TRM1*(1.0-TRM2) F=T*PI P=(WT*SIN(ALPHA+PHI)-F*COS(ALPHA+PHI))/ COS(ALPHA+PHI+DELTA) PH=P*COS(DELTA) IF(PH.LT.0 : OR. PH.GT.1000)GOTO 20 IF(PH.GT.PMIN)GOTO 21 C IF(PH.LE.PMIN)ALPMIN=ALPHAD IF(PH.LE.PMIN)PMIN=PH WRITE(22.*)AL.ALPHAD.PMIN.PH ALPHAD=ALPHAD+1 CONTINUE 20 WRITE(21,22)AL, VO, ALPMIN, PMIN FORMAT(5X, IL=, F34, 2X, VOL, SURCHARGE=', F9.7, 2X, 21 22

1 Total Bole we have the set of the

1

1 'ALPHA=',F5.2,2X,'PH=',F8.5) 10 CONTINUE STOP END

216

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C THIS PROGRAMME CALCULATES THE FRONT FACE RESISTANCE C FOR MODEL MS USING COLLOMB'S METHOD. THE COMONENTS C OF PASSIVE AND FRICTIONAL RESISTANCE ON TWO INCLINED C FACES IN THE DIRECTION OF MOVEMENT IS CONSIDERED.

OPEN(UNIT=19.FILE='EXP.DAT', TYPE='OLD') OPEN(UNIT=20 FILE='EXP.ANS', TYPE='NEW') READ(19.*)N DO 5.I=1.N READ(19.*)AL.VO GAMA=17.0 AK0=0.5 B=0.25/COS(67.5*3.142/180.0) RHO=0.0 D=(AL-0.302)/35.0 VO=V0/2.0 WRITE(20,7)AL.2.0 VO FORMAT(2X.'TRIANGULAR WEDGE',//,'SCOUR LENGTH=',F4.2.5X, 'VOL OF OVERBURDEN='.E8.2) PHI=35.5*3.142/180.0 DELTA=23.0*3.142/180 BETA=1.637*3.142/180.0 RHO=RHO*3.142/180.0 C TOTAL WEIGHT = WT. OF VARIABLE WEDGE + WT. OF OVERBURDEN WT = WW + WOWO=GAMA*VO TITAD=5.0 TETA=TITAD*3.142/180.0 WW=GAMA*B*(0.5*(D*COS(BETA))**2*COS(RHO+TITA) 1 /COS(RHO+BETA)/ SIN(TITA-BETA)) WT = WW + WOTYPE*.'WW='.WW.'WO='.WO.'WT='.WT P=(WT*SIN(TITA+PHI))/COS(TITA+PHI+DELTA+RHO) PH=P*COS(RHO+DELTA) C ** FOR TRIANGULAR PRISM PH=PH*0.7749*2.0 WRITE(20r9)TITAD, WO, WW, WT, PH FORMAT('FOR TITA=',F4.1,2X,'WO=',E8.2,2X,'WW= 1 E8.2,2X,'WT=',E8.2 ,2X,'P=',F9.4) TITAD=TITAD+1.0 IF(TITAD.LE.30)GO TO 10 CONTINUE STOP END

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Allen Billion





LOAD . CELL

SCALE: FULL SIZE

Kistler Model 912 Quartz Dynamic Load Cell

Specifications:

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Range: compression
Resolution
Overload
Sensitivity (nominal)
Resonant frequency (nominal)
   (no load)
Rigidity
Rise time
Linearity (zero based best
   straight line)
'Capacitance (nominal)
Insulation resistance (minimum)
Temperature sensitivity
Temperature range
Side force (maximum)
Shock and vibration
Cable connector, side coaxial,
   teflon insulation ....
Case materials
Weight .
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Land States

5000 lbs (2268 kg) 0.002 lb (0.9 gr) 20% 50 pcb/lb (110 pcb/kg) 70,000 Hz

20x10⁻⁸ in/lb (1x10⁻⁸m/kg) 5 microsec 18

58 picofarads 10¹³ ohms 0.01% per *F -400 * to 300*F 100 1bs (45 kg) 10,000 g 10:32 thread

416 SS, 17-4PH SS 0.6 oz (17 gm)



10-32 THD. COAXIAL CONN

PRESSURE TRANSDUCER



Kistler Model 606A/606L Quartz Pressure Transducer

Specifications:

Range full scale Resolution Maximum pressure Sensitivity (nominal) Resonant_frequency (nominal) Rise time Linearity (zero based best straight line) Capacitance (nominal) Insulation resistance Acceleration sensitivity Temperature effect on sensitivity Temperature range Shock, 1 ms pulse width Case material Weight

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606A*

3000 psi (21 MPa) 0.005 psi (0.03 KPa) 5000 psi (34 MPa) 5.5 pcb/psi (0.8 pcb/KPa) 130 KHz 3.0 microsec 18

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50 picofarads 10¹³ ohms <0.005 psi/g (0.03 KPa/g), <0.03% per *F

-350° to +450°F 1000 g SS 0.5 oz (14 gm)

*Model 606L is identical to 606A except for range of 30 psi and maximum pressure of 300 psi 30 psi equals approximately 207 KPa 300 psi equals approximately 2068 KPa CALIBRATION

All the pressure transducers and load cells used in this investigation were originally factory calibrated and were recalibrated by Charl (1975) and Green (1984). However, the calibration was rechecked both at the beginning and end of the superimental work. Load cells were subjected to direct compressive stall force using Instron Testing Machine. Keeping the amplifier under long time constant, a static force was applied in increments of 1 kN, over sufficient length of time and the response was monitored. Pressure transducers were calibrated using a piston activated oil pressure chamber and also by using a mercury column. In all the repetitions, good consistery was observed indicating the reliability of the pressure transducers.







