ICE FORCES AGAINST ARCTIC OFFSHORE STRUCTURES

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I. BACKGROUND

This first quarterly report covers progress on the subject contract from December 1, 1981, the date of inception of the study, until March 1, 1982.

The objective of the research program is to determine the lateral forces on artificial islands and offshore structures which are subject to moving sea ice. This is particularly oriented towards the exploration and development of Arctic oil and gas deposits in the Beaufort, Chukchi, and Bering Seas. A recent report (National Petroleum Council, 1981) estimates that there is a risked mean value of 30.8 billion barrels of oil equivalent to be found in this ice-infested offshore region, encompassing some 262 million acres.

The approach taken is to measure the effective ice stress at relatively large distances from such islands, to measure the ice displacement simultaneously, and to determine the effective island width, during ridge building events which represent intervals of high lateral force on the island or structure. Both experimental measurements and their analytic interpretation are expected to be of central importance in the certification of proposed designs for Arctic islands and drilling structures.

Ice forces against structures have been of concern for decades to designers of bridges and dams in ice-covered rivers. The major hazard to bridge piers is in the form of freshwater ice, nominally at 0°C, moving downstream during the spring breakup. A review of design practice for such situations has been given by Neill (1976), who reported maximum effective pressures of 1970 kN/m^2

(260 lb/in^2) on vertical piles and about 1240 kN/m^2 (180 lb/in^2) on an inclined pier.

The first producing offshore oil platforms in Cook Inlet, Alaska, were designed to withstand the forces of moving sea ice. The vertical cylindrical legs were designed for 2070 kN/m^2 (300 lb/in^2) design load, and Blenkarn (1970) reported that the instrumented structures were subject to sustained pressures of less than 860 kN/m^2 (125 lb/in^2) and peak ridge loading of less than 1035 kN/m^2 (150 lb/in^2). Failures of Swedish and Finnish lighthouses in the brackish ice of the Gulf of Bothnia, on the other hand, were calculated to have resulted from ice pressures of 160 mt/m^2 (228 lb/in^2) in one case, and 67 to 125 mt/m^2 (95 to 178 lb/in^2) in another case (Reinius et al., 1971). Considerable uncertainty with respect to friction coefficients between the ice and the structure (estimated at 0.03 to 0.56) led to the wide range of estimates in ice stress at the time of structural failure. An instrumented lighthouse in the Gulf of Bothnia has detected local ice pressures of up to 250 N/cm^2 (363 lb/in^2) but local pressure variations on the monopod resulted in a reduction factor of 30% to 60% in total lateral load compared to that calculated from this peak pressure (Maattanen, 1977). These steel and concrete structure concepts may be extended to the more severe ice loading conditions of the Beaufort and Chukchi Seas, but greater lateral forces are to be expected there because of thicker and stronger ice. For example, Burns et al. (1980) have reported multiple rafted annual ice in the Bering Sea near St. Lawrence Island with a thickness of 10 meters, which compares with a nominal thickness of 1.3 meters for ice in Cook Inlet. A thesis by Karp (1980) uses a nominal 32 meter multiyear ice ridge thickness for the Chukchi Sea, although ice ridge keels of 52 meters depth are presumed to exist based upon ice gouging of the sea floor. Multi-year ice is stronger than annual ice, and initial calculations of lateral forces against steel cylindrical structures yield very large values.

The strength of multi-year ice remains to be determined in detail, and is the subject of an active research program (Cox, 1981). Alternative structure designs which have been considered, some of which are being put into practice, include artificial gravel islands and conical steel or concrete structures. In the Mackenzie Bay region of the Canadian Beaufort Sea, and in the Alaskan Beaufort Sea, artificial gravel islands have found widespread usage in the past decade. The appropriate design method to be used to calculate lateral forces due to ice motion for such islands remains to be determined, however. The problem is compounded by several factors which are difficult to address in detail except by a statistical method. For example, the ice around an artificial island is constrained at the island boundary, and is frozen to the gravel beach. Tidal fluctuations in sea level cause the formation of at least one and often several tide cracks around the edge of the island. If the island is of a shape other than circular (e.g. rectangular) then additional cracks running radially outward from the island are observed. The island surface is usually from one to three meters above the water line, which induces the accumulation of drifting snow on the ice sheet just beyond the island boundary. This adds to the gravity load, depressing the ice sheet, and the insulating effect of the snow inhibits the further growth of ice at that location. Early in the winter, the ice sheet may move against the island if it is in an exposed location, causing the formation of an ice ridge on one side of the island and the creation of an open water lead on the opposite side of the island. Repeated thrust sequences of the ice sheet, driven by winds acting over large distances, tends to build pressure ridges around the island which have been termed "ice rubble" (Kry, 1977). The ice in the rubble field usually extends to the sea floor where it is grounded, and it offers some additional resistance to lateral motion of the ice sheet. It appears that additional ridgebuilding occurs at the outer edges of the rubble field, implying that the lateral force on the island itself would be less during successive thrust events. The largest force would be expected at the time of the initial ridge building sequence. Obviously, a wider island would be subject to a greater total force. The problem resolves itself into devising an appropriate method for calculating that force.

A conservative approach has been given by Ralston (1979) in which the ice sheet is assumed to be of uniform thickness and frozen (without cracks) onto the island boundary. The formula presented by Korzhavin (1962) was modified as:

$$F = k\ I\ \bar{\sigma}\ b\ t$$

where F is the lateral force, t is ice thickness, b is diameter, k is the contact factor (k = 1 for perfect contact), and I is the indentation factor. A plastic limit analysis has resulted in an upper bound of I = 3 in columnar ice and I = 1.2 in granular ice. For ice crushing, σ has been taken to be the unconfined compressive strength, which is a function of salinity, temperature, strain rate, and ice type. In fact, the value of unconfined compressive strength to be used is subject to a great deal of engineering judgement, in view of the variations in the ice thickness, temperature, and geometry at the island boundary. The strain rate dependence of the uniaxial compressive strength of annual sea ice has been investigated by several authors (Michel and Toussaint, 1977; Wang, 1979). Even if one knew the precise dependence of compressive strength upon strain rate, it is clear from the foregoing discussions of the cracks in the ice that buckling failures are much more common than compressive failure, and that compressive failures occur only in very localized areas prior to buckling and ridgebuilding events (Kry, 1977).

Measurements have been made of the stresses in sea ice near artificial islands and natural islands (Nelson and Sackinger, 1976; Sackinger and Nelson, 1978; 1979a; 1979b; Metge et al., 1975; Metge, 1976; Templeton, 1979a; 1979b). The gauges which have been deployed have differences in geometry and stiffness. However, the single outstanding feature of all of the gauge deployments in the field is that only stresses in the ice sheet in the vicinity of the gauge are measured by the gauge. Most installations were near some shoreline or fixed obstacle (such as an island or a grounded ice pile). Their local readings have been invariably affected by local variations in stress concentration due to cracks or island boundary irregularities. In such instances, the calculation of total force on an island really requires the simultaneous data from a great number of sensors; because of financial constraints; it has often been impossible to deploy a reasonable number of sensors.

Deployment of sensors at great distances from an island involves long signal cables or telemetry links. However, the ice stress at great distances is subject to less local variations due to island boundary effects and associated local crack patterns. Fewer sensors are required to make a credible estimate of the spatially-averaged ice stress. This is likely to be quite low, far below failure, since failure occurs at the island boundary first. However, the average stress at large distances from the island does translate into the total force upon the island (and its associated ice rubble) by means of the complex transfer of stresses through the cracked and nonuniform ice near the island.

The specific information needed is the appropriate value of effective ice stress, σ_{eff}, to be used in Korzhavin's equations, and the effective width, b_{eff}, over which the stress operates upon the island. The viewpoint in which one considers the average stress at great distances from the island, and the gross movement of the ice toward the island, may be termed a "mesoscale" viewpoint, and the stresses may be termed "geophysical" stresses. If the effective width of the island and the effective geophysical stresses are known, they can be used in Korzhavin's equation to give the total force on an island without regard to the non-linear transfer function and the variable stress concentrations which are adjacent to the island boundary. The major objective of the research program is to verify this viewpoint and to establish appropriate values for b_{eff} and σ_{eff}. Thus, the total force upon an artificial island can then be calculated.

Such an approach can then be used for estimating the ice force upon an artificial steel or concrete structure which is subject to either a moving multi-year ice ridge or an ice island. In one mode of failure of a consolidated multi-year ice ridge, the ridge rides up the surface of a conical structure and fails in flexure. However, in another possible situation, the consolidated multi-year ice ridge rests solidly against a structure and the annual ice sheet behind the multi-year ridge begins to fail in buckling. The formation of ridges of annual ice in that instance represents the same type of lateral loading sequence as if the consolidated multi-year ridge were a grounded island. Research results from studies around an island can be extended to this situation as well, and the lateral force on the artificial structure can be predicted.

Specific experimental information is to be obtained for the prediction of lateral forces on islands and structures, using the approach discussed above. In particular, the sea ice stress levels, over a broad front, at a distance far from the island, are to be measured as a function of time. The movement of the ice sheet (related to crack closure and ridgebuilding) is to be measured simultaneously as a function of time. Also, the environmental conditions (wind speed and direction) which cause this movement are to be recorded. In the following section, the details of the equipment to accomplish these specific objectives are discussed.

II. MESOSCALE ICE STRESS/STRAIN MEASUREMENT SYSTEM

In order to measure representative values for σ_{eff} and b_{eff}, one must install several ice stress measurement stations relatively far from an island. The distance should be from three to five times greater than the island diameter (using St. Venant's Principle) to avoid the region of stress concentration and cracking. At the same time, the movement of the ice sheet (the "geophysical strain") must be measured continuously, between the stress stations and the island. Finally, the wind speed and direction should be measured, since it represents the driving force, and a threshold for the initiation of the ridgebuilding process. (Earlier experiments have shown that a windspeed of greater than 10 knots acting for several hours is usually sufficient to cause ice stress buildup and crack closure, depending on the distance over which the shear stress of the wind acts upon the ice sheet.) The three parts of the experimental system will be discussed in more detail below.

Ice stress measurements have been made since the pioneering research of Nelson ten years ago (Nelson et al., 1973; Nelson, 1974; Sackinger et al., 1974). He developed a uniaxial cylindrical-shaped ice stress transducer, with a modulus stiffer than the ice. A small strain within the gauge is sensed by foil-type strain gauges, and the stress concentration in the ice around the stiff gauge is determined from experimental calibration of the sensor when it is embedded in a large block of ice and the ice is subject to a known load. These gauges have been installed and operated in a variety of locations since 1973, including Barrow, Prudhoe Bay, Kuparuk River Delta, Pt. Thompson, Narwhal Island, and the Chukchi Sea in Alaska, and Adgo and Netserk Islands in the McacKenzie Bay in Canada. Tests have been conducted at Resolute Bay, Eagle Lake, and near Niakuk 3 using these gauges. The most recent version (Biswas and Sackinger, 1980) is very sensitive (1 p.s.i.) temperature-compensated ($\pm$ .2 psi over -20°C to +20°C), and capable of sensing stress variations at frequencies up to 20 Hz. Telemetry links are used to transmit the data in real time to a central station for digitizing and recording. Sufficient equipment is available from earlier projects to install 9 channels of uniaxial stress instrumentation at three locations. Assuming planar stresses in the ice sheet at these three locations, this would permit the deployment of three sites with a rosette of three gauges at each site. These gauges are to be given a routine calibration check, embedded in an ice block, and loaded at 0°, 45°, and 90° to the gauge axis, before installation. This calibration will be accomplished in two phases; one phase will be in a laboratory loading press, at a controlled strain rate, and the second phase will be by means of a flat jack, in the actual ice sheet in the field. In this way, the exact calibration of the stress concentration factor and tranverse sensitivity of the sensors will be confirmed.

A new concept in ice stress instrumentation is embodied in the six-element gauge invented by Sackinger and Goodman. At a given point in the ice sheet, six measurements are needed to determine the stress tensor completely. (If planar stress is a valid assumption, then only three measurements are required.) The six-element gauge consists of two rings, with three strain-gauge bridges mounted on each ring. This gauge will be calibrated in an ice block as described above, and then one of these gauges will be installed at a single field site to verify that the intuitive assumption of planar stresses is in fact justified.

At the end of the first quarter, nine uniaxial stress sensors from earlier projects were checked and prepared for calibration in ice blocks. In addition, two ring sensors were constructed, and appropriate methods for waterproofing the rings were developed. These were prepared for calibration as well, and were integrated into the entire ice stress measurement system which is described in the following sections. However, calibration of the sensors still remains to be done in the second quarter of the program. The installation of the complete calibrated systems will not be possible during April 1982, as originally hoped, but the thoroughly-calibrated system will be ready for installation early in the winter of 1982-83.

It should be pointed out that several other types of stress sensors have been developed within the industry, each with its own advantages and disadvantages. This program is not oriented towards a comparison or calibration of those gauges, which is a very ambitious subject, but rather will provide rationale for the choice of installation sites, and the stress levels associated with ridgebuilding.

Ice movement in the shorefast zone has been measured extensively by Spedding (1975; 1979) who made use of a system referencing to a fixed location on the sea floor. This approach involved two fixed weights on the sea floor which were connected by wire lines extending through a tube inserted in the ice sheet. The wires were attached to potentiometers which then convert the mechanical movement to an electrical ouput. Tidal signals appeared on both channels of such an instrument and were subtracted out, resulting in data on the movement direction and magnitude of the ice sheet.

It is essential that two movement stations be deployed far from the island. The decision was made early in the program to concentrate on islands in deep water where pack ice, moving relatively rapidly, should cause higher forces. Large movements (1 km/day) are consequently expected and it became apparent that devices used by Spedding would not have sufficient dynamic range for more than a few hours of vigorous movement records. After considering all of the other position-sensing devices commercially available, only the microwave positioning systems and the acoustic positioning systems seemed to be appropriate. The acoustic systems, as used on dynamically-positioned drill-ships, suffer from high cost and a limited displacement range. Among the microwave systems only the Motorola Mini-Ranger was guaranteed to operate at the ambient cold temperatures expected in the Arctic. Hence, this system was examined carefully. The positioning error of the system depends upon the length of the reference baseline for the system. Two reference stations separated by a fixed, known distance are required. If these are located on a single artificial island, and are 100 meters apart (limited by island size), then a site on the ice 1 km from the island would have a position error of $\pm$ 20 m. The minimum positioning error is achieved when the distance to the ice station is one half of the length of the baseline; in this example, a baseline of 100 m and a distance of 50 m yields an error of ± 2.8 m. A 50 m distance is much too close to the island for the stations, because of ice ridge and local island effects as discussed at length above. This logic leads one to the conclusion that a baseline length of the order of 2 km or more is essential to make use of the microwave positioning system in an effective manner. On the other hand, the range is limited by the line-of-sight, and by equipment output power, to a maximum distance of 37 km. The optimum locations for the two reference stations would be (a) on the artificial island of concern, and (b) on a nearby natural or artificial island, or the shoreline itself.

Arrangements were made with Dome Petroleum Ltd. and Gulf Canada Ltd. to install the system, if it were ready, in April of 1982 at their new caisson-retained island, Tarsuit, in the Canadian Beaufort Sea, since there were no artificial islands in the Alaskan Beaufort Sea in the 1981-82 winter season which were located beyond the barrier islands, exposed to moving pack ice. The cooperative spirit of Dome Petroleum has been remarkable. Unfortunately, the position of Tarsuit, some 64 kilometers from shore, makes it impossible to locate two reference stations within line-of-sight of each other unless they are both on Tarsuit itself; the consequence of this is the unacceptably large position error (± 20 m) mentioned above. Since the schedule for stress gauge calibration presently projects completion at the end of the second quarter, it is not possible to install the complete system at Tarsuit during the late winter (April) of 1982 as was initially hoped. Everything will be thoroughly ready for deployment in the winter of 1982-83, however, and a site in the

Alaskan Beaufort Sea, presently under construction within line-of-sight (5 km) of a natural island will hopefully be available for this project. In that case, a positioning system accuracy of ± 2.8 m is expected.

A block diagram of the ice measurement system is shown in Figure 1. Three ice sites collect data and transmit it by FM telemetry to the central fixed island location, where a receiver and discriminator package provides 15 channels of data to the sampling and digitizing unit. Wind and ice position information are also provided and a redundant sampling and local printout check is provided by having a Fluke 2240 B data logger in parallel with the main Crememco unit. Sampling rates of 5 times per second for each channel are presently programmed for the Cremenco unit, based mainly upon the data storage economics and logistics. This can be changed later in the program if faster data rates are needed. The Fluke sample rate is much slower, (1 channel in 2 seconds) depending on output printing, but provides a real-time system check on-site. All equipment in Figure 1 is available at no cost to this project, and only the positioning system will have to be either leased or purchased. System assembly and checkout has been completed in the laboratory, with electrical inputs at the ice sensor level showing corresponding outputs from the plotter of the VAX computer. Further calibration tests are in progress. All equipment, with the exception of the positioning system, is on hand, functional and in the system calibration stage.

III. PLANS FOR SECOND QUARTER

During the second quarter, system calibration will be completed. The calibration of ice stress gauges will be a major effort. Details of interfacing the positioning system with the data acquisition computer will be completed, and discussions with Shell Oil Company about the possibilities of 1982-83 deployment near their Seal artificial island location in 39 feet water depth in the Alaskan Beaufort Sea will be undertaken.

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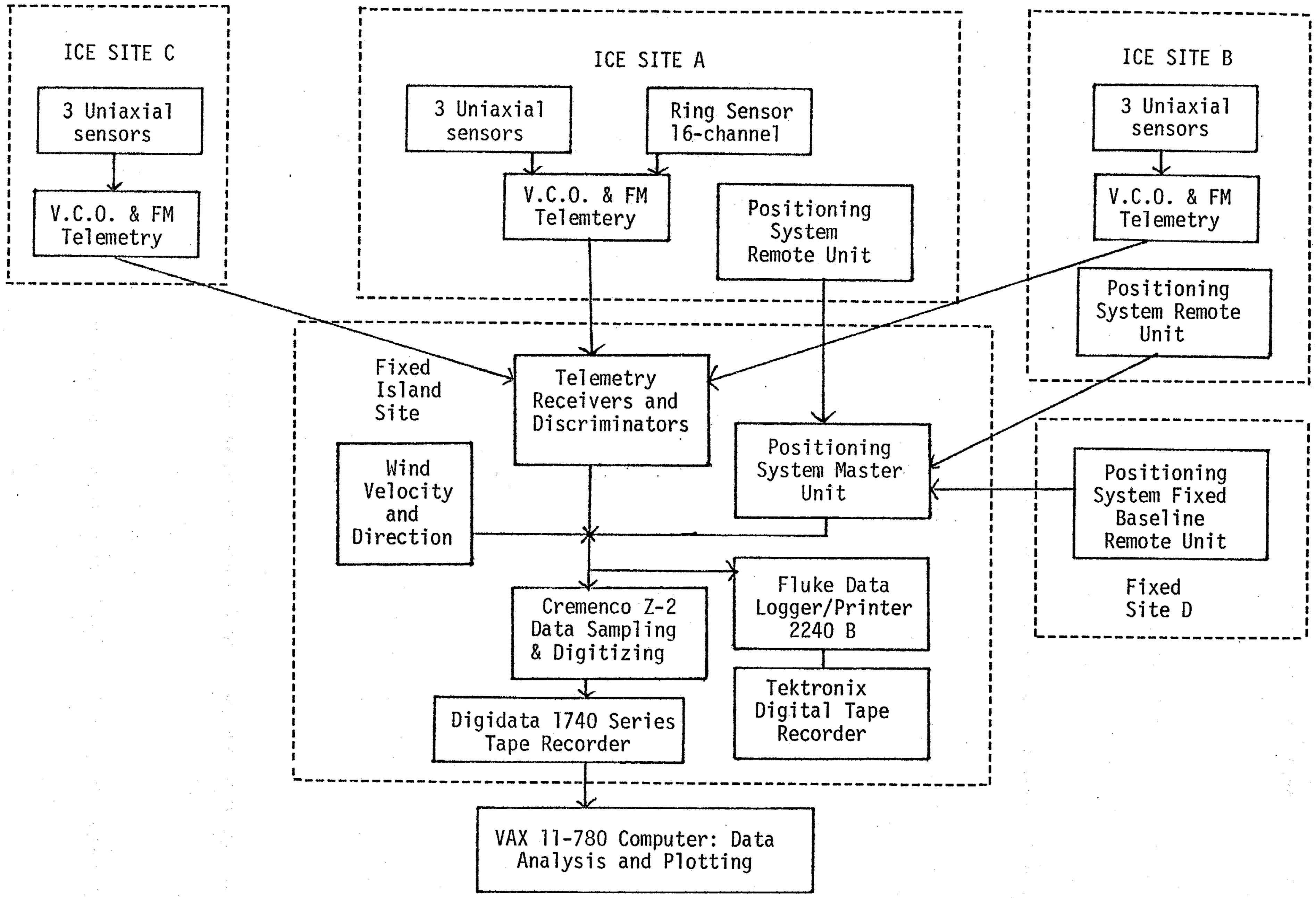

Figure 1. System Diagram for Mesoscale Ice Stress and Displacement Measurement near Artificial Islands

Figure 2. Ice Forces Project Flow Chart