Ice Island Study

Final Report

MMS Project #468

APPENDIX A

Prepared for:

Minerals Management Service
US Department of the Interior

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THE ICE ISLANDS PROJECT (MMS)

31 October 2003

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Sandwell

GROUNDED ISLANDS

GEOTECHnical resources ltd. / GOLDER & ASSOCIATES
CLIENT: SOHIO PETROLEUM COMPANY et al
REPORT DATE: SEPTEMBER, 1985

Construction, Testing & Monitoring Spray Ice Island (Main Report) (MARS)

Overview:

The objectives of the project were as follows:

Evaluation of the influence of construction factors (e.g. environmental conditions, pumping equipment and procedures, etc.) on the quality and quantity of spray ice produced.

Evaluation of conventional and novel techniques for drilling and sampling, in situ testing and performance monitoring.

Evaluation of the macro-performance of a full scale spray ice island.

Development of a constitutive model for describing the behaviour of spray ice based on in situ testing together with laboratory testing on both undisturbed and reconstituted samples.

Preparation of a factual report summarizing the data obtained together with preliminary evaluation of construction techniques, sampling, in situ and monitoring techniques and laboratory data.

The island was constructed in a 30 day period in February and March, 1985. The grounded portion of the island had the following dimensions:

Diameter	-	350.0 ft.
Average Freeboard	-	16.5 ft.
Water Depth	-	30.0 ft.

The planned sampling, in situ testing and monitoring installation programs were completed between April 2 and 11, 1985. Monitoring of island performance was continued on a periodic basis until June, 1985. The laboratory program on undisturbed samples was carried out at the same time as the field work while testing on reconstituted samples was carried out in Calgary after the field work was completed.

Construction

The island was designed to resist a global ice load of 137 kips/ft assuming that the below water spray ice had zero cohesion and an effective angle of shearing resistance of 30°. It was assumed that excess porewater pressures would not develop during shear. Based on the calculated design volume and an efficiency of 60%, a large capacity pump (3800 US gpm) and a smaller capacity pump (1000 US gpm) were selected for construction and were housed in skid-mounted containers. Spraying operations and monitoring during construction (i.e. build-up, ice temperature, environmental data) were carried out on a 24 hr/day basis with two personnel on each of two shifts. Thermistors, flatjacks and piezometers were installed during the construction process. Samples were obtained for calorimetry experiments and studies were made of drop size formation.

It was the intent that spraying would produce as uniform a material as possible. The freshly deposited material would be such that 1-2 in. deep footprints would be formed. However, it was found that a wide variety of environmental and operational factors affected both production rates and material type. Wind speed and direction together with air temperature were the significant environmental factors. Spray direction relative to wind direction, vertical angle of spraying and nozzle setting were important operational factors. The large pump performed satisfactorily and with small modifications is suitable for spray ice island construction. The smaller pump was generally ineffective and pumps of this nature (centrifugal) and capacity should not be used for future construction.

During the first two weeks of construction, an average build-up rate of about 1 ft/day was achieved. With increased experience and equipment modifications an average build-up rate of 2 ft/day was achieved in the second half of the construction period. During a 3-day period of relatively warm weather production rates were low. The overall efficiency achieved in construction, defined as (volume of spray ice/volume of water pumped) was about 43%.

A significant feature of the spray ice island was the development of cracks during construction. The majority of the cracks occurred when the base of the island grounded on the seabed. Only two significant cracks remained within the grounded portion of the island following completion of construction; monitoring indicated that these cracks were not active.

The total direct cost of island construction including mobilization/demobilization, equipment development, pump rental, accommodation, etc. was about $560,000 U.S. This represents a unit cost of about $3.50 to $3.80 U.S./yd^3 in place, but does not include the cost of subsequent investigation and monitoring.

Investigation Program

The investigation program involved the following:

- 9 Sampled boreholes - sampled using Shelby tubes, the Delft continuous sampler and a specially designed sampler.
- 14 Cone penetration tests (CPT) using a 3 channel acoustic cone (700 ft of useable record).
- 51 Self-bored pressuremeter (SBP) tests in 3 boreholes.
- 1 In situ falling head permeability test.
- 8 Horizontal flatjack panel installations to determine vertical total stress.
- 6 Vertical flatjack panel installations to determine horizontal total stress and stress-strain behaviour.
- 24 Borehole jack tests in one borehole above water level.
- 4 Slope indicator casings.
- 3 Sondex settlement systems
- 3 Piezometers
- 2 Thermistor strings
- 52 Thermal drill holes to map the underside topography of the island.

The following is a summary of observations related to the useability of the individual investigation and monitoring techniques:

Drilling - Penetration using a 6 in. diameter solid stem auger yielded entirely satisfactory borings. Boreholes remained open above the water level, but freezing occurred at the water line.

Sampling - Shelby tubes were used with mixed success - this approach is suitable for softer layers, but tubes tended to buckle in the harder layers.

- The Delft continuous sampler provided reasonable to good quality samples provided lubrication/pressure equalization fluid between the "sock" and liner was not used.
- A special thick-walled steel sampler, which freezes the bottom of the sample, was developed for this project and provided good quality samples.
- Samples of both above water line and below water line materials were obtained in a relatively undisturbed state.

Sample Transportation

- Local (near site) transportation of both saturated and unsaturated samples was successfully achieved using brine barrels.
- Samples were successfully transported from site to Calgary in refrigerated trucks.

Cone Penetration Testing

- This was a highly successful technique which provides an excellent definition of in situ stratigraphy (i.e. consistency variations). Minor equipment modifications would further enhance future CPT work.

Self Bored Pressuremeter Testing

- After experience was gained in the first borehole, these tests could successfully be carried out.

Flatjack Tests

- Horizontal flatjacks did not work effectively because the pressure associated with the fluid-filled line was greater than the in situ vertical stresses. Vertical flatjack installations were more effective.

Borehole Jack Tests

- These tests were effective in above water materials only; the stroke of the equipment was not adequate for testing the below water line materials, partly due to the enlarged borehole diameter.

Falling Head Permeability Tests

- These tests provided reasonably credible data but boundary conditions are not well defined.

Monitoring Installations

- Slope indicator casings, Sondex settlement casings and piezometers were effective and no major problems were encountered with their operation. Backfilling around instruments installed in boreholes was not effective. Only two of four thermistor strings operated effectively; problems associated with these installations can be readily overcome.

Site Investigation Results

Geometry

- The grounded portion the island was about 330 ft. in diameter. Side slopes to sea ice level varied between 2.5(H):1(V) and 6(H):1(V). Below water slopes are reversed (i.e. sloping under the island) at 5(H):1(V) to 3(H):1(V).

Stratigraphy

- The above water materials consist of relatively uniform size (0.04 in. diameter) white or clear ice granules. Significant layering was observed with layers of ice rich material and layers of essentially granular material. The below water materials were wet. Below water ice granules were typically clear and slightly larger than above water granules. Much of the below water material comprised frequent harder/bonded layers although the intervening material had little or no cohesion.

Density

- The density of above water materials increased from about 35 pcf at surface to 47 pcf at the water line. The density of below water materials was difficult to determine because of pore fluid loss during sampling and a wide range in density (40 - 63 pcf) was obtained.

Salinity

- The salinity of the above water materials ranged between 0 and 1%. The bulk salinity of below water samples was higher (0.5 - 1.5%) because of the presence of saline pore fluid (1.9 to 2.4%).

Frozen Content

- Calorimetry experiments on the below water samples indicated a frozen water content of 70-90% by weight, which is slighty greater than would be expected based on the density of the above water materials.

Cone Penetration Tests

- The measured tip resistance during CPT penetration was highly variable ranging from close to zero over some depth intervals to an average minimum of 215 - 285 psi. Friction ratios were relatively low at about 0.5 - 1%. Excess porewater pressures were not recorded during cone penetration; hydrostatic pressures were measured below the water line. The cone tip resistance provided a good indication of stratigraphy but a poor measure of in situ strength.

Self-Bored Pressuremeter Tests

- These tests yielded consistently high values of modulus and maximum inflation pressure. This was in contrast to the CPT results and reflected the fact that the tested zone in an SBP test incorporated both strong and weak layers. Creep rates observed in SBP tests were proportional to inflation pressure when expressed on a log-log plot.

Permeability

- The falling head permeability test indicated a coefficient of permeability of 3×10^{-4} to 3×10^{-3} ft/sec. These values are typical of a clean sand or sand/gravel material, which is consistent with the grain size of spray ice. However, because of difficulties in defining test boundary conditions, these permeability values are only approximate.

Flatjack Tests

- Interpretation of the vertical flatjack tests indicated high modulus values (average based on 10 tests of 13400 tsf). These high values reflect the fact the stiffness of the harder layers.

Borehole Jack Tests

- These test were carried out in above water materials only and indicated plate pressures typically in the range 26 to 31 tsf. Locally soft zones were observed at some depths.

Instrumentation and Monitoring Results

Temperature

- The above water temperatures varied with air temperature and at depths near surface varied from 28°F to -30°F. Temperatures at sea level were fairly constant at 29°F. The below water spray ice temperature was relatively constant with depth and throughout the monitoring period remained at about 29°F.

Porewater Pressures

- Significant excess porewater pressures were not recorded during the monitoring period.

Lateral Deformations

- Significant lateral movements were not recorded with depth through the island (slope indicator casings) nor on the island surface (direct surveying).

Vertical Settlement

- About 1 ft of settlement of the island surface occurred in a two month period. The settlement rate decreased only slightly with time during this period. The Sondex casings indicated that settlements were concentrated in the vicinity of the water line but these data may be affected by non-uniform freeze-back around the casings.

Crack Monitoring

- Monitoring of the major crack remaining following construction indicated only slight relative movements (less than 1.5 in.) across this feature.

Ablation

- Until late May, when air temperatures rose to above freezing, negligible ablation or ice degeneration was noted. The island remained relatively intact until July.

Constitutive Behaviour of Spray Ice

Triaxial tests were carried out on both undisturbed and reconstituted samples of spray ice. Testing of undisturbed samples was generally carried out under in situ conditions. The testing conditions for reconstituted samples were varied to determine their effect on material behaviour. The results of testing on reconstituted samples provide the basis for a behavioural model for spray ice under both drained and undrained conditions as follows:

Strength

- The ultimate shearing resistance of spray ice is controlled by the effective stresses existing in the sample. Failure conditions are represented by a linear failure envelope in q-p' stress space. The final location on the failure envelope (i.e. the shearing resistance of the material) is controlled by the porewater pressure response during shear which varies depending on factors such as strain rate and length of the consolidation/creep period prior to shear. Temperature conditions also affect strength.

Stress-Strain Behaviour

- Typically for most test conditions, the initial response of spray ice to load application is small strain followed by a reasonably well defined yield. Following yield, the observed stress-strain behaviour was generally either plastic or strain hardening behaviour depending on test conditions. Although the data are scattered because of varying test conditions, it appears that yield occurs within a narrow range of stress ratio.

Time Dependency

- Spray ice is a highly time dependent material as is evidenced by plots of normalized strength and porewater pressure parameters vs strain rate in strain controlled tests, and in the variation in failure envelopes depending on time related test factors. Stress controlled creep tests also exhibit strong time dependency. However, creep rates are low and relatively constant up to yield. At higher stress ratios, creep rates increase with increasing stress ratio.

Compressibility

- Under drained conditions, spray ice is highly compressible, even at low stresses. However, given its high permeability, spray ice consolidates rapidly; most of the observed volume change under load is due to creep.

The stress conditions in the triaxial test control the strength which is measured in relatively competent natural materials (i.e. undisturbed samples). The shear strength of these materials is high and is dependent on initial density. Tests on weak natural materials indicate failure states which lie on the failure envelope observed in laboratory tests on "aged" reconstituted samples.

Conclusions and Recommendations

Construction

- The construction phase of the operation was successful in that useful information related to construction of spray ice islands was obtained and the final island was suitable for investigation and monitoring. Recommendations related to future island construction are provided.

Investigation and Monitoring

- These programs were successfully completed and recommendations related to future work of this nature are provided.

Preliminary Design Recommendations

- Based on the results of this project and previous experience, it is reasonable to expect that spray ice islands could be used for offshore hydrocarbon exploration in the Arctic. Strengths can be developed to sustain design ice loads and deformation can be maintained within acceptable limits. Construction cracks do not present operating difficulties. However, it should be appreciated that only limited understanding of spray ice is available and experience related to the performance of full scale structures is meagre. Therefore, considerable further effort is required to improve the current status of knowledge involving these materials including both the basic physical processes which govern its macroscopic behaviour and the engineering behaviour of the material.

  Notwithstanding the above, the results of this project clearly identify two major areas of concern with respect to island design as follows:

1. Variability of material type and consistency is a major feature. Thus, weak layers, which can be considered to be effectively continuous over the plan area of the island, will control design. The question is - what is the shearing resistance in these materials? Tip resistances measured in cone penetration tests are, in some cases, close to zero; possible reasons for this phenomenon are discussed. It is

concluded that the strength of these apparent weak layers is not zero - strengths can be calculated from the behavioural model developed from laboratory test data with due regard for deformation criteria. The large strengths and stiffness of both below and above water materials indicated in large volume tests (i.e. SBP, flatjack tests) are not appropriate for design.

2. Spray ice is a highly time dependent material. Therefore creep deformation under sustained vertical and lateral loading is a major design consideration. At present, little data are available to permit extrapolation of laboratory or field creep data to higher stress levels and protracted time periods which, for example, would be associated with rig loading.

McCLELLAND-EBA, Inc.
CLIENT: AMOCO PRODUCTION COMPANY, DENVER
REPORT DATE: October, 1985

Design Basis MARS Spray Ice Island

Background

Amoco Production Company plans to construct a spray ice island in Harrison Bay, Alaska, during the 1985-86 winter season. The island will stand in 25 feet of water and will serve as a temporary platform for exploration drilling. Pre-design feasibility studies have shown that with normal weather conditions, a 60 day drilling season will be available after pad construction and drill rig mobilization. Construction of the spray ice island will commence about December 15, 1985 and the island will be ready for occupancy by February 1, 1986. A one-week period will be provided prior to spudding the well for verification testing to ensure compliance with the design.

Multi-year ice features are infrequent or can be avoided at the site, therefore the design ice load has been derived from movement of the first-year ice sheet past the island. Local failure within the spray ice initiates bending and pile-up of the natural sea ice. Once flexural failure is initiated in the ice sheet, the maximum ice load that can be transferred to the spray ice island is that associated with building of rubble at the sea ice/island contact. With provision for a sacrificial fringe on the spray ice island, the maximum global ice forces that can be transmitted to the island will be less than those associated with ice crushing against a fixed, rigid structure.

Engineering data for design of the spray ice island were obtained from a prototype island constructed during the winter of 1985. Properties of the spray ice were determined by sampling and in situ testing. Strength properties were determined from unconfined and confined (triaxial) testing. These data were supplemented by temperature, settlement and lateral displacement monitoring.

Island Geometry

The proposed island has an outer diameter of 944 feet. Included within this dimension is a 400 foot diameter centrally-located drill pad, a 152 foot wide berm and a 125 foot wide ice/island interaction fringe. The berm surrounds 75 percent of the drill pad perimeter. The drill pad will have an end-of-construction elevation of +20 feet and the berm an elevation of +40 feet. The interaction fringe rises from sealevel to a maximum elevation of +5 feet. To account for settlement over the 60 day operation period, the island has been designed with two feet of overbuild on the drill pad and three feet on the berm. A 100 foot diameter helipad and 80 foot wide 1V in 20H access ramp are positioned on the southern perimeter of the drill pad. The island design configuration and construction specifications are provided in Drawing 4242-1, Appendix A.

Island Stability

The island is designed for a horizontal ice load of 100 kips per foot of projected width. This is equivalent to a global ice load of 94,400 kips acting on the structure. The global force is resisted by the strength of the island and the shear resistance that can be developed at or near the island/seabed interface. Drained and undrained sliding resistance has been examined. The critical condition for the island is dependent on the drained (frictional) resistance that can be mobilized in the spray ice near the seabed. A factor of safety of 1.5 against lateral island translation has been obtained for the island weight acting on a horizontal spray ice surface with an angle of internal friction of 30 degrees. Factors of safety greater than 4.0 are calculated under undrained loading conditions on a clay seabed.

Rig Foundation Stability

The spray ice behaves as a visco-elastic material. It deforms under a constant load at a rate that is predictable using creep theory developed for ice and permafrost soil. The amount of creep settlement is dependent on the creep parameters, the magnitude of the applied load, and the duration of load application. For a given set of creep parameters, increases in load magnitude or load duration will result in larger settlements.

The maximum average vertical stress in the drill pad area due to self-weight is about 720 psf. The highest applied rig load, derived from the substructure of the derrick, is 900 psf. Based on numerical modelling, this component is estimated to settle about 2 feet during the proposed 60 day well program. Differential settlements between various components are anticipated to be less than 1 foot. The settlements will develop slowly, allowing time for maintenance if necessary.

A timber rig foundation system that allows circulation of cold ambient air below all heated structures has been developed. This foundation system will distribute the rig loads and eliminate heat transfer to the underlying spray ice.

Construction Varification and Monitoring

A comprehensive verification and monitoring program is recommended during construction of the island and subsequently during drilling operations. The program has two main objectives: to ensure that the island is constructed to meet the conditions and criteria adopted for the design; and to permit safe operation of the island under the imposed environmental conditions.

Construction verification is achieved through observation and control of the island geometry during construction, and quality assurance testing of the spray ice properties. Control of geometry will require precise position surveying prior to and during construction, and subsequent monitoring of as-built island dimensions.

The size and elevation of the island components specified are minimums. Over building is acceptable but under building of either size or elevation will require review of the design analyses.

Operational monitoring should include ice/island interaction observations, lateral deflection measurements, temperature changes and settlements. The performance of heated surface facilities is of particular importance. The program must provide early detection of adverse temperature changes within the spray ice platform that could accelerate creep settlements.

GEOTECHnical resources ltd.
CLIENT: CHEVRON U.S.A. Inc.
REPORT DATE: November, 1988

Design Basis Karluk Prospect King Spray Ice Island

Overview:

DESIGN BASIS OF

CHEVRON KARLUK PROSPECT KING SPRAY ICE ISLAND

GEOTECHnical resources ltd.
CLIENT: CHEVRON U.S.A. Inc.
REPORT DATE: November, 1988

Design Basis Karluk Prospect King Spray Ice Island

Chevron's Karluk grounded spray ice island will be located in Stefansson Sound at the co-ordinates N70° 19.44737', N147° 30.3193', as shown in Figure 2.1.1.

The island is located approximately 20 nautical miles northeast of Deadhorse in twenty four feet of water.

Access to the island, during construction and drilling, will be provided by 13.5 miles of ice road with approximately 8.5 miles of the road floating. The road will be routed to avoid the boulder patch as shown in Figure 2.1.1., and will be staged from the Endicott causeway.

The ice road design requirements are included in Chevron Karluk Ice Island - Construction Methodology, reported by GEOTECH, 1988.

The road routing, thickness specifications for the anticipated loading conditions and markings are specified in Drawing No. 9600-D-002.

A detailed ice physical environment and meteorological report for the Chevron Karluk site was prepared by Vaudrey and Associates and is included in Appendix A.

The report provides historical and statistical data on ice and meteorological conditions necessary for establishing:

- o Mobilization and Demobilization Planning
- o Ice Island Construction Strategy
- o Design Criteria for establishing horizontal design loads for the island.

The Mobilization and Demobilization planning and Ice Island Construction Strategy is discussed extensively in Chevron Karluk Ice Island - Construction Methodology, reported by GEOTECH, 1988.

The design criteria for establishing the horizontal loads for the grounded ice island is presented in Section 3.1.

GEOTECHnical resources ltd.
CLIENT: CHEVRON U.S.A. Inc.
REPORT DATE: November, 1988

Design Basis Karluk Prospect King Spray Ice Island

Harding Lawson Associates prepared a detailed geotechnical report for the Chevron Karluk site location. The report is included in Appendix C. A generalized subsurface profile and geotechnical properties for the site is presented in Figure 2.3.1.

The lateral stability and bearing integrity of the ice island, as controlled by the foundation, is based on the data included in this report and is discussed in Section 3.3.1 and Section 3.3.2 respectively.

The design parameters for the foundation in the finite element modelling of the island (included in Appendix C) is based on the data included in the Harding Lawson report.

Laboratory and field data is available to evaluate the elastic and strength parameters of spray ice above water line.

The elastic and strength parameters established for design is based on data available from the following sources:

o Panarctic's Buckingham 0-68 Platform, reported by GEOTECH, 1984
o Panarctic's N. Buckingham L-71 Platform, reported by GEOTECH, 1986
o Panarctic's N. Cornwall N-49 Platform, reported by GEOTECH, 1986
o Sohio Test Island, reported by GEOTECH and Golders, 1985.

SANDWELL SWAN WOOSTER INC. / CATCO
CLIENT: CHEVRON U.S.A.
REPORT DATE: September, 1989

Karluk ice Island Project Report

Overview:

In 1988, Chevron U.S.A. as operator with Mobil as a partner decided to drill an offshore well near Prudhoe Bay, Alaska using a grounded ice island as the drilling structure. Ice Construction and Engineering (I.C.E.), a Joint Venture between CATCO, a division of Crowley Maritime, and Sandwell Swan Wooster (SSW) designed and constructed the ice island for Chevron. The construction and monitoring were conducted by I.C.E. under a turnkey, fixed price contract, the first time this type of contractual relationship had been attempted for an ice island project.

The island was located 7 miles ENE of Cape Brower in 21 feet of water. The island was built by spraying sea water using 20 m^3/min. (5000 g.p.m.), 1400 kPa (200 p.s.i.) pressure pumps equipped with nozzles and swivels. An island with a total thickness of 14 m (46 ft.) and a diameter of 270 m (890 ft.) was designed and built. Unfactored, design lateral ice loads of 1370 kN/m (92 k/ft.) were used for the stability analysis. Ice loading was the dominant design force. The ability of the ice island to support the rig and associated supplies and equipment in bearing was also assessed. The design included mechanical systems to protect against thawing of the ice by heat generated by the drilling activity.

Construction of the 20 km. (12.6 mile) ice road began on November 19, 1988. By December 12, the ice thickness was sufficient to mobilize the island construction equipment. Construction of the island began on this date with the required volume of ice in place by January 20, 1989.

Between January 20 and February 2, 1989, the island surface was prepared, the integrity of the island was verified and the instrumentation required for the monitoring program during drilling was installed. Drilling began February 20, 1989 and rig release was April 7, 1989. During construction, ice build up, ice volume constructed, pump moves and position, water volume pumped, ice temperature and ice density were monitored. Daily progress was reported and daily contour maps were plotted to help in planning the next days activity. During drilling, horizontal ice movement, vertical ice settlement, ice temperature under the rig and meteorological conditions were monitored. Most of the data was logged in real time using a custom built data acquisition system.

The project is described in five (5) separate reports. For convenience, these five reports, initially issued to Chevron as individual reports, have been bound into one document for limited distribution to Chevron and the Joint Venture partners.

SANDWELL SWAN WOOSTER INC. / CATCO
CLIENT: CHEVRON U.S.A.
REPORT DATE: September, 1989

Karluk ice Island Project Report

The **QUALITY CONTROL REPORT** describes the quality control procedures in place to ensure that the island would meet the design specifications. The results of the program are also included.

The **VERIFICATION REPORT** describes the measurements taken, once the island was completed, to certify that the island satisfied the design specifications.

The **INSTRUMENTATION REPORT** describes the instrumentation and data acquisition system installed at the end of construction to monitor the engineering performance of the island during drilling.

The **ENGINEERING PERFORMANCE REPORT** describes the performance of the island from construction completion through to rig out.