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A FEASIBILITY STUDY INTO MONITORING DEFORMATION IN THE NIGLINTGAK REGION OF THE MACKENZIE DELTA

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Abstract

This paper reports on a feasibility study for the monitoring of both natural trend, and subsidence due to gas extraction, in the continuous permafrost area of the Mackenzie Delta in Northwest Canada. A base study, including hydrological and cryo-geological considerations was performed, followed by the examination of different types of monitoring method, both areal and point observation, and their potential to solve the particular problems associated with monitoring in this area.
A solution was sought that would be able to be implemented without extensive further research work being undertaken. For this reason, a rigorous DGPS solution was recommended, with further studies being made into the required geometry of point monuments, their stability in permafrost over the period of the monitoring regime, and the performance of DGPS in the measurement of subsidence at latitude of 69 degrees north.

1. Introduction

Until relatively recently, analysts in the energy sector had dismissed the economic need to develop the large natural gas fields (estimated at 65 trillion cubic feet) in the Mackenzie River Delta of the Northwest Territories in Canada (Wright Mansell Research Ltd, 2002). Since 1988, however, certain developments have arisen that have brought renewed interest in the area from potential gas-field developers. Feasibility studies are therefore currently underway into the development of the gas-fields, for instance the joint study undertaken by Imperial Oil Resources, Gulf Canada Resources Ltd., Shell Canada Ltd, and Mobil Canada Ltd. These studies are not only focussed on the regulatory and fiscal requirements, but also on the potential environmental impact of any development.

This paper reports on a feasibility study undertaken to analyse the possible subsidence monitoring regimes that could be implemented in the Niglintgak Island area of the Mackenzie Delta. Particular emphasis is placed on the role of permafrost activity in the monitoring process, and how this affected the analysis and recommended regime. The study was undertaken by six academics, from three departments, at the University of Calgary.

2. The area of monitoring

Figure 1 shows a map of Canada highlighting both the area of interest, and the distribution of permafrost. The study area is in the zone of continuous permafrost and is subject to significant levels of ground ice content. Niglintgak Island lies approximately 150 kilometres north of Inuvik at a latitude of 69° 20’ North and a longitude of 135° 20’ West. Figure 2 is a view of the southern portion of the island, with an overlay of the predicted most-likely scenario for the subsidence in the area due to gas reservoir depletion during gas extraction. This was developed by the client using bore-site log analysis, together with a client-proprietary geomechanical modelling code. The asymmetry of the subsidence bowl is due to the presence of faulting in the NE-SW direction. Figure 2 also shows that the area is part of the Kendall Bird Sanctuary, an important nesting area for around 100 species of migratory birds. The area has been extensively studied by environmentalists, leading to a high awareness of the potential impact of land-use in the area.

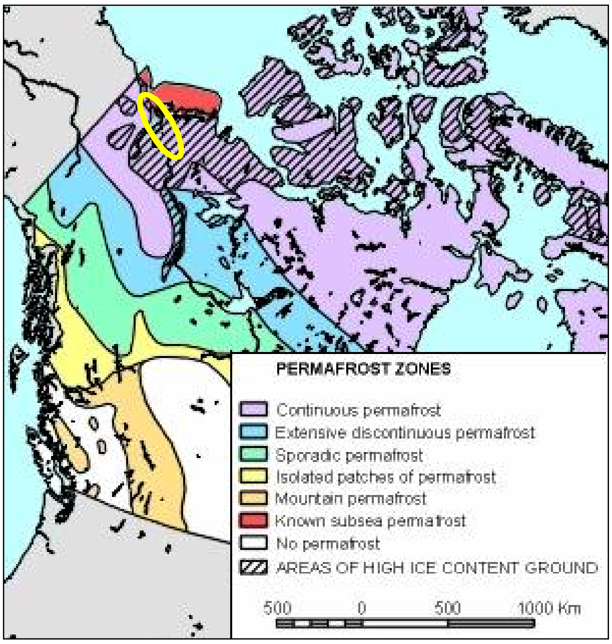

Figure 1 Distribution of permafrost in Canada (Natural Resources Canada, 2003). Area of interest is indicated by ellipse.

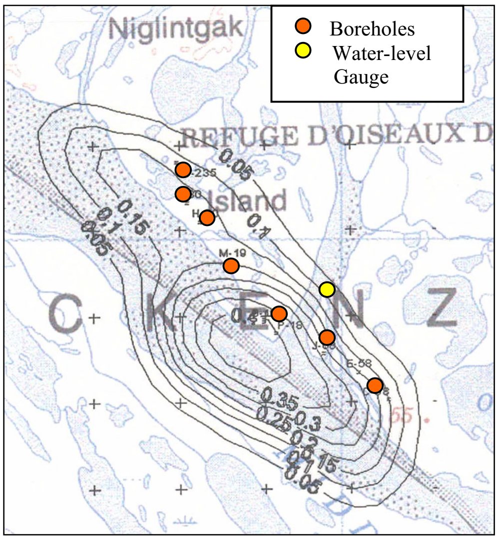

Figure 2 The location and extent of the predicted subsidence bowl

A number of difficulties in the planning of a monitoring method arose immediately from the configuration and remote location of the target area;

1. A large part of the subsidence bowl was predicted to form beneath the Kumak Channel to the South of the island (Figure 2). High rates of sedimentation in the channel, together with the presence in the sediment of large ice volumes (Traynor and Dallimore, 1992), made it unlikely that hydrographic measurement could confirm the subtle movement that could be expected in this case,

2. Despite a complex hydrology in the area, consisting of spring floods due to ice-jamming, and storm surges from the Beaufort Sea, there was insufficient existing data from tide and river gauges to be able to predict a 50 year flood event, considered the minimum required for a 25 year monitoring period,

3. The annual freeze/thaw of the active layer above the permafrost in this area has been observed at the 20cm level (Mackay et al, 1979), with a wide variation in timescale

dependant on such factors as annual snow cover, atmospheric conditions, and vegetation growth.

4. Topographic maps of the area were available; a 1:50,000 scale (Army Survey Establishment, 1958) and 1:250,000 scale (Energy, Mines and Resources Canada, 1988). With contouring every 50 foot interval these maps gave almost no information on the elevations of the area to be monitored. In addition, a rate of hydraulic erosion in some southern areas of the island of 2.5m per year (Traynor and Dallimore, 1992) makes these maps quite obsolete for the purposes of locating, for instance, stable areas for monumentation.

3. Requirements for the monitoring regime

The requirements for the monitoring regime were in two parts. Firstly, the natural trend in the area should be established so that underlying processes could be isolated from the subsidence due to gas production. Secondly, the predicted formation of the subsidence bowl should be regularly confirmed, to ensure that no other mechanisms than the relaxation of the reservoir due to pressure depletion were being activated by the extraction.
There was little evidence to support analysis of the natural trend in the target area. One study on the heave/thaw cycle, conducted over ten years at five locations in the region, showed an average settlement of 1.4 cm per year in the near surface (Nixon, 2002). However, the sparse nature and variability within this data indicates that there is an appreciable range in thaw settlement across the region.
In terms of mechanisms other than the reservoir reaction to pressure depletion, the major causes of concern were the possible development of 'transient taliks' (perrenially thawed zones), by inundation of the permafrost through flooding. This can result in subsidence rates that are measured in tens of centimetres per year. Not only would land settlement need to be measured, but also the flood risk for the area (chosen as a 50 year risk as stated above). Only through such a combined approach could the true processes involved in any unpredicted subsidence be monitored and subsequently ameliorated.
Despite the lack of reliable elevation data for the island (Traynor and Dallimore, 1992) indicated that these channel banks rarely exceed 1.5 MASL.

A hydrological monitoring regime was proposed to augment the (incomplete) five years of data available from the water level gauge in Middle Channel (see Figure 2). 3-5 years of additional data would be required before statistical analysis would be advised. Regression methods in conjunction with an upstream station, established in 1982, might also be possible after this period. Although tidal influences were assessed to make insignificant contribution to channel level, storm surges from the Beaufort Sea would have a greater influence (Marsh and Schmidt, 1993). For this reason it was recommended that a tidal gauge should be established at the mouth of the channel (10 km from the area). Together with the additional water-level observations, this would allow a 50 year flood risk to be assessed for the area.

4. Analysis of monitoring methods

Based on a production life of 25 years, it was predicted by the client's geomechanical model that subsidence due to extraction will occur only in the 10-25 year period. Assuming linear rates of subsidence over this 15 year period, a maximum yearly vertical displacement of around 2.7cm would occur. A simple congruency analysis (95% confidence, Fisher test for 1D and assuming a known probability density function [PDF]) resulted in a 1σ observation accuracy of 9.7mm being required to find significant movement in the central point on an annual basis. In the absence of a natural trend, or the less likely case of a higher than predicted subsidence due to compaction coefficient reliability, this is the limit case required for the monitoring network.

A number of potential solutions, using both terrestrial and satellite-borne sensors, and considering both permanent and annual measurement campaigns were considered.

4.1 Areal methods

In view of the inability to make observations in critical areas of the subsidence, such as along the axes and centre of the anticipated bowl, an areal method that would reduce the need to interpolate points between observations was initially examined.

With the launch of the Envisat radar altimetry satellite, and that of the laser altimeter vehicle ICESat, new opportunities exist for topographic measurement in the North of Canada. The 98.5° inclination and 35-day repeat cycle of the Envisat means total Earth coverage on a monthly basis if necessary. Radar altimetry for the measurement of land surfaces is a relatively new area of study, however, and has been observed to have accuracy in the observation of water surfaces of only 3cm (Chelton, 2001). Water surfaces have a well-understood distribution of scatterers, whereas land surfaces provide echoes of unpredictable, and rapidly changing shape, making interpretation difficult.

Differential Interferometric SAR has the capability of sub-centimetre observation of subsidence, and has been used to measure permafrost active layers (Wang and Li, 1999), yet the biggest unknown in the error budget for these sensors is temporal decorrelation (Strozzi et al, 2001). Temporal decorrelation has been found to be almost total in other permafrost areas after less than 24 days (Moorman and Vachon, 1998), in areas of lower vegetation than that present in the target area. It is thus unlikely that any temporal correlation would exist in the target area for any of the satellite return periods.

Overriding these potential sources of error in either altimetry or D-INSAR is the need, using an areal method, for a mathematical model of the permafrost active layer. This would be a fairly straightforward achievement accomplished using observations of surficial geology and vegetation, using a DEM and dominant wind patterns to model snow accumulation, and calibrating with the limited data that is already available. The precision of such a model would only be in the 1-2cm range, however.

4.2 Monumented methods

Since an areal method would not achieve the required accuracy for an annual monitoring campaign, a monumented point solution was sought. The problem of geometry of the monumented network and the long-term stability of these monuments in a surface subject to annual heave and settlement is the subject of Section 6.

Precise levelling was examined as a potential solution, in both absolute and relative networks. In the former case, it was already recommended that a sea-level gauge be installed to monitor for storm and tide influences on the Kumak Channel, so a datum would be established for an absolute network. However, sight lines across water courses, to close traverse lines, would sometimes exceed 2km.

For a potential relative network, trend signal analysis (Kenselaar and Quadvlieg, 2001) allows a network that is constrained using one of the unstable benchmarks in the test area. Trend signal analysis has so far been estimated only for extraction from reservoirs with a depth/diameter ratio of 1, although work is progressing to characterise the trend signal for several irregular reservoirs (Quadvlieg, 2003).

In-situ monitoring using pipe or cable extensometers was also considered. There are some boreholes remaining in the area from the geological survey (see Figure 2). Extensometers can be both accurate (in the order of 0.5mm) and cost-effective (when placed in existing boreholes).

However, neither type is very accurate if the borehole exceeds 0.5 degrees from vertical (Poland, 1984). Unfortunately, the boreholes present in the target area do not meet this requirement.

DGPS is a well established method of monitoring subsidence with velocities measured in the 2 – 20mm range, with an accuracy of one tenth of the velocity values (Rothacher and Mervart, 1996). This type of survey requires careful planning, extensive fieldwork, and rigorous post-processing. Annual campaigns were considered feasible, therefore (see Section 5).

Continuous monitoring using GPS was also assessed. There are plenty of examples of CGPS used in the analysis of long-term deformation, for instance (Hudnut et al, 2001). In addition, there are those that have been established in sub-arctic areas, for instance the SWEPOS system (Hedling et al, 2001). The establishment of these permanent stations included the creation of heated concrete pillars connected to bedrock, and an instrument hut with full instrumentation rack, in addition to the provision of TCP/IP communications and external power sources. This approach was considered unfeasible by the client since implementing a relatively large number of such stations, together with the problem of lack of communications in the target area, presented serious logistical and cost issues.

5. Recommended monitoring regime

Since it was desirable to have both vertical and planimetric measurements of deformation, due to the possibility of shear on production platforms, a monumented solution using DGPS observations was recommended. This solution was judged to have the highest short-term probability of success in monitoring the subsidence; short-term in this sense meaning requiring the minimum extra research work to implement the system.

The proposed field regime would employ a number of geodetic-quality, dual-frequency receivers with a base station at the Canadian Active Control System (CACS) station at Inuvik (CACS Products, 2002), which has been found to be one of the most stable monuments in the entire Arctic (Craymer, 2002). The baseline thus formed would be 130km, the shortest distance available to a CACS station from the target area. With the base receiver established at Inuvik, each monument would be occupied for 24 hours to allow correction of ionospheric errors. The receivers would use the semi-codeless techniques to track the P code on the L2 carrier phase, to improve retention of satellite lock in the event of scintillation effects on receiver performance, of great importance in the Arctic region (Skone et al, 2001). Choke rings will be employed to minimise multipath, and phase-centre offsets and their variations calculated prior to the field campaign.

Since the estimated accuracies of GPS static surveys are often optimistic, due to a large number of degrees of freedom, combined with the typical approach of neglecting the time correlation between observations, each monument will be reoccupied for the same period on another day to give an external assessment of the quality of the position results.

Post-processing of independent baselines will use Bernese GPS software Version 4.2 using carrier phase double differencing to eliminate ionospheric error. Additionally, this software has extended functionality to model tropospheric path error. Final precise orbits from the International GPS Service will be used in the orbit parameter generation. L1 and L2 carrier phase pre-processing will enable the detection and repair of cycle slips and unpaired observations. A daily solution will be computed, after which a final solution based on the combination of normal equations will be calculated using the constraint of the Inuvik base station. This will allow a comparison of the co-ordinates of a daily solution and those of re-occupied points, giving a measure of external accuracy for the survey.

A 24 hour occupation, plus a return period of the same duration, might be reduced after the first few sets of data have been examined for the accuracy of positioning, although a day's occupation would seem indicated at these latitudes by others work on the influence of changes in diurnal ionospheric activity (Krankowski et al, 2001). There is also some concern that vertical dilution of precision at this latitude, estimated using Trimble Total control software, is 3-4 for the majority of a 24 hour occupation. These issues are further discussed in Section 6.2.

6. Further studies

6.1 Surface modelling

Due to the inability of making observations in critical areas of the subsidence bowl, a study was performed to assess the number and location of point observations needed to simulate the anticipated subsidence bowl. Using ArcGIS Geospatial Analyst, a base surface was first fitted to the predicted subsidence bowl shown in Figure 2. The base surface was fitted with a maximum standard error of less than 1mm.

The contour data was digitised and registered using a similarity transformation. Initial analysis of the digitised contour data demonstrated a regional trend in the data. While it is possible to use Universal Kriging to generate trend surfaces, ArcGIS does not allow control over the trend surface used. For this reason, a trend surface was fitted using a third order polynomial, this was then subtracted from each test case of monumentation, Ordinary Kriging applied to the residuals, and then the trend surface added back into the solution. In this way, since the trend surface would be the same in each case each resulting model could be compared directly. Four models, of different monumentation geometry, were calculated in this way and compared to the base model.

Comparison between base and model surfaces was carried out at 95% confidence, and using a Fisher Least Significance Difference (LSD) method to determine which of the four modelled surfaces most adequately conformed to the PDF of the base model. On these criteria, a model has been suggested that has a maximum difference from the base surface of 7cm in the centre of the bowl at 95% confidence, but with 73% of the 205000 grid cells showing no significant difference at this level.

The main drawback of the models generated in this way is that the method assumes zero error in the point observations. Clearly measurement error, and error in the stability of the monuments, will affect the number and geometry required for the monuments. The following section addresses these issues.

6.2 Determining the errors for the surface model

A field campaign is planned at Inuvik, Northwest Territories, to establish the error budget in the proposed monitoring regime that may then be used to model surfaces, and hence monument numbers and configuration, in a more rigorous way. The campaign will measure, using both precise levelling and DGPS, a set of 30 permafrost monuments established by Geodetic Survey Division (GSD) Canada from 1977 onwards. These monuments comprise seven different monument types, from tablets established on concrete foundations to steel double-sleeved, oil-filled permafrost benchmarks. These monuments have been measured using precise levelling up until 1995, but the results have not been analysed for stability of monument. A new epoch of measurement, in combination with the previous observations, gives the potential to analyse the stability of these different monument types over a period of nearly 30 years (approximately the period of monitoring required for this project).

In addition, the DGPS campaign will allow the analysis of the effect of satellite geometry on the estimation of height at 69 degrees north. The effects of ionospheric delay at this latitude will also be evaluated, in conjunction with ionospheric observations from GPS receivers currently being placed to improve estimation for real-time applications (Skone, 2002).

The results of this error analysis will be applied to the surface model, using a covariance matrix approach to the solution of the semi-variogram for the Kriging of surface models.

7. Conclusions

This paper has reported a desk study on the requirements and methods of monitoring natural trend, and subsidence due to gas extraction, at Niglintgak Island in the remote north of Canada (69 degrees North). This area is one of very changeable nature, comprising annual permafrost heave and settlement, high rates of sedimentation and erosion of the low-lying surface, and a complex and variable hydrology.
Since the significant areas of the predicted subsidence bowl lie underwater, an areal method was preferred to allow high sample rate with which to form surface models of the subsidence. Permafrost active layer modelling would only give an accuracy of 1-2cm, however. Since an annual campaign was required by the client, and since the required accuracy for the limit case would be only around 1cm, areal methods were precluded.
The monitoring regime recommended, therefore, was an episodic DGPS campaign on point monuments. Surface fitting using Geospatial Analyst functions of ArcGIS have been used to determine the configuration of the monument network required to simulate the subsidence bowl using discrete point data. Currently, these models assume no observation error. Further work is underway to characterise the error budget arising from the geometry of GPS satellites at this latitude and the ionospheric effects on the quality of positioning estimation. At the same time, the stability of different types of monument in permafrost will be observed and analysed.

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