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ORIGINAL PAPER

STUDY OF NATURAL AND MAN-INDUCED GROUND DEFORMATION IN MACKENZIE DELTA REGION

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ABSTRACT

Withdrawal of natural gas is being planned in the area of lower Mackenzie River Delta in northern Canada. The subsidence caused by the gas withdrawal is predicted to reach about 0.5 m within the next 25-30 years. Due to the low laying land, the ground subsidence may result in hydrological changes and flooding of large areas that is of a major concern to environmental protection. A monitoring scheme is being designed to verify the prediction models. One of the important tasks of the monitoring scheme will be to separate ground subsidence due to gas withdrawal from the total surface deformation resulting from natural causes such as permafrost degradation and post-glacial isostatic or tectonic uplift/subsidsence of the area. Global Positioning System (GPS) and satellite Interferometric Synthetic Aperture Radar (InSAR) are being considered as the main tools of monitoring.

1. INTRODUCTION

Development of gas production fields north of Inuvik in Mackenzie River Delta of the Northwest Territories in Canada (Fig. 1) are planned for the development at a total cost of CDN $ 16 billion (Council of Canadian Academies, 2008). The gas withdrawal will result in a depletion of pressure in the gas reservoirs resulting in a compaction of the reservoirs (Chrzanowski and Szostak-Chrzanowski, 2010). The compaction will produce deformation of the overburden rocks and eventual subsidence of the ground surface, which is estimated to reach 0.5 m over the next 25 years. The subsidence may cause extensive flooding of low-lying large marshy delta of the Mackenzie river that is of a major concern to Environment Canada (Robertson and Schellekens, 2009). The area is bird-nesting for around 100 species of migratory birds and is a calving area for Beluga whales. In order to control ground deformation, a monitoring scheme has to be designed to verify the ground subsidence prediction models. Harsh climate conditions, very deep permafrost (up to 700 m), degradation and settlement of permafrost due to warming effects, complex tectonics and difficult access to the area must be considered in designing the monitoring scheme to give reliable results with the sub-centimetre accuracy. One of the important tasks of the monitoring scheme will be to separate ground subsidence due to gas withdrawal from the total surface deformation resulting from the natural causes such as uplift or subsidence of the ground surface caused by post-glacial rebound, sedimentation loading, tectonic stresses, long-term permafrost degradation due to climate change, ocean tide loading and loading and unloading caused by hydrological changes.

2. NATURAL GROUND DEFORMATION IN MACKENZIE DELTA

2.1. *NATURAL SUBSIDENCE/UPLIFT DUE TO ISOSTATIC OR TECTONIC ACTIVITY*

According to geological evidence (Peltier, 2002; Peltier, 2004), the northern region of Canada shows a coherent pattern of postglacial isostatic adjustment, which continues to the present day. The adjustment pattern has been plotted in Figure 2 from data given in (Andrews, 1989). The Mackenzie Delta lies within the western subsidence zone. In the Mackenzie Delta region, other factors such as tectonic activity and faulting may also contribute to vertical motion.

A 45 years record of water level gauge at Tuktoyaktuk, indicates that the relative sea level is rising at a rate of +3.5 mm/y. At the same time, recent results of long term GPS observations at the Tuktoyaktuk Active Control Point (ACP) indicate relative land subsidence at a rate of -2.8 mm/y ±1.1 mm (Craymer, 2010) with respect to Inuvik ACP, which is monumented in bedrock about 130 km south of Tuktoyaktuk. Thus, the difference between the sea level rising and the land subsidence may be within the errors of measurements or may indicate a combined effect of both.

Since 2005, about 20 GPS stations have been installed in permafrost across Mackenzie Delta. The

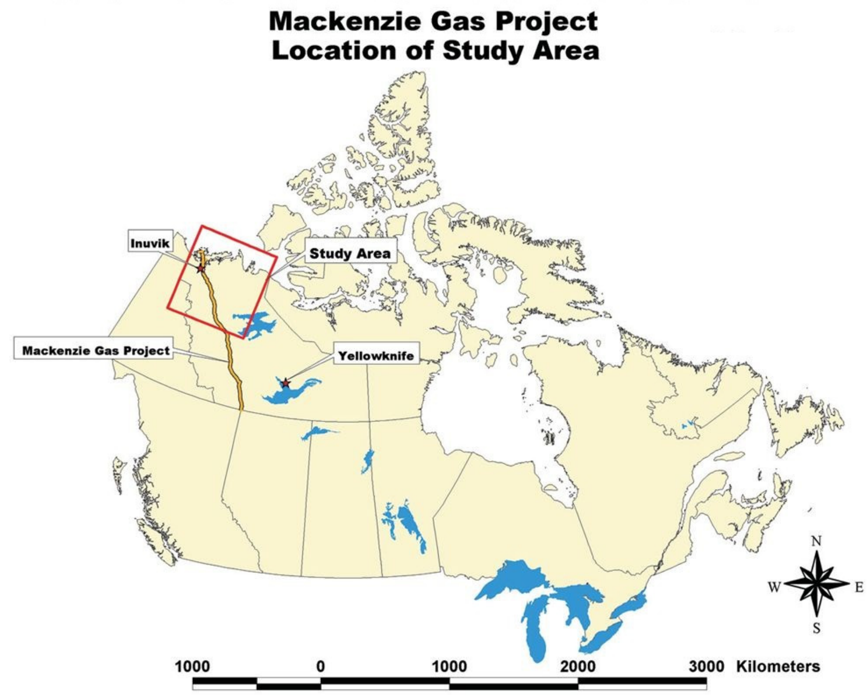

Fig. 1 Location of Mackenzie Gas Project.

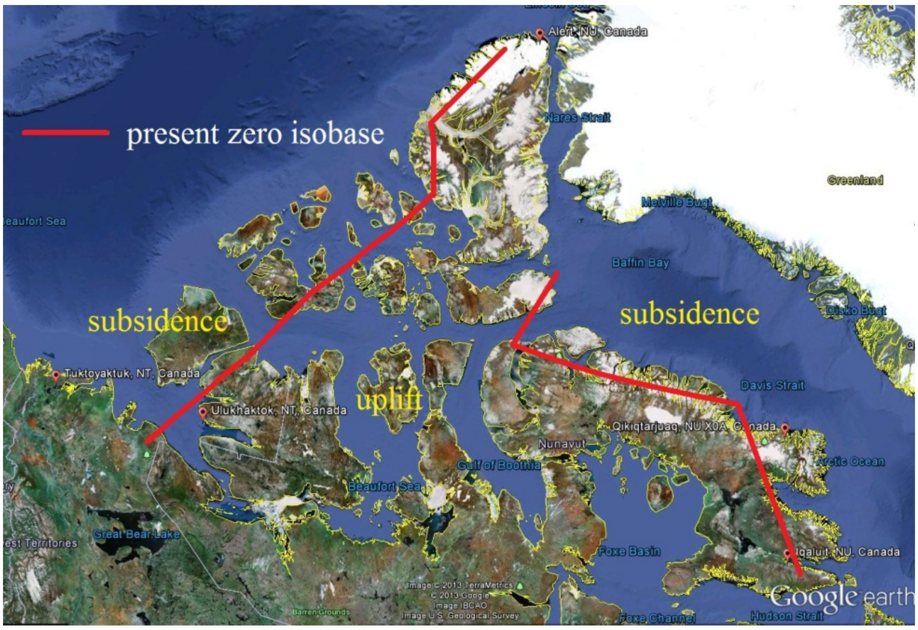

Fig. 2 Postglacial isostatic adjustment (subsidence/uplift) in northern Canada (google Earth).

stations were installed with 25 mm diameter pipes jet-drilled into permafrost to the depth between 10m to 30m (Craymer, 2010). Figure 3 shows one of the GPS stations. During the summer months, the stations can be accessed by boats and during the long winter period, ice roads are maintained for overland transportation from Inuvik. Preliminary results from 8 GPS stations indicate that the whole area is subsiding with respect to Inuvik station at an average rate of – 3.7 mm/yr (Chrzanowski and Szostak-Chrzanowski, 2010; Craymer, 2010). It is still to be explained whether the land subsidence is of a tectonic origin or is an effect of sediment compaction.

2.2. *SEASONAL AND LONG-TERM DEFORMATIONS OF PERMAFROST*

One of the most important components of ground deformation in Mackenzie Delta is the seasonal heave and settlement of permafrost, which may reach decimetre levels, and the suspected

Fig. 3 One of GPS stations in Mackenzie Delta area (photo courtesy D.L. Forbes, Geological Survey of Canada).

systematic settlement of the surface due to the global warming effect and degradation of the permafrost. In the area of the planned gas withdrawal, a non-homogenous permafrost reaches a depth of 700 m with non-ice bonded sediments under larger bodies of water.

Degradation of ice-rich permafrost can lead to the most significant surface subsidence. Hydraulics and terrestrial hydrological processes in the northern latitude regions are controlled by the presence or absence of permafrost and the thickness of the top active layer of soil that thaws and freezes in seasonal cycles. Beneath the active layer and within the permafrost are layers and vertical bodies of unfrozen material called *talik*. Compaction in the upper part of the subsurface in the modern delta is limited by permafrost and ice-bonding, but can occur at greater depths and in the taliks below lakes and channels.

In the Mackenzie Delta, the air and ground temperature is increasing (Osterkamp and Romanovsky, 1999; Wolfe et al., 2000, Smith et al., 2001). If the warming trend of a total of 1ºC over the past 13 years continues, then permafrost could degrade over the next decade. Thawing of ice-rich permafrost can result in thaw settlement and subsidence of the ground surface and development of uneven and frequently unstable topography.

The seasonal cyclic thawing and freezing of the active layer causes cyclic settlement and heave at decimetre levels. Mackay et al. (1979) reported seasonal heave of up to 20 cm. The depth of penetration of seasonal thawing in the Mackenzie Delta is in the order of 1 to 2 metres. This imposes some restrictions on monumentation of survey markers. The current monumentation of the GPS stations with 25 mm diameter pipes drilled-in to the depth of 10m – 30m gives very good vertical stability. However, horizontally, some of the stations give erratic results. Use of sturdier pipes of a diameter of 2.5 inch (ca. 63 mm) drilled-in to the depth of 15 m have been proposed by Chrzanowski and Szostak-Chrzanowski (2010).

The seasonal deformation and possible long-term systematic settlement of the thawing/freezing active layer due to warming effects and degradation of permafrost is the major unknown in evaluating the total surface deformation in the region.

3. PREDICTION OF GROUND SUBSIDENCE DUE TO GAS WITHDRAWAL

The Mackenzie/Beaufort Sea region (Fig. 1) is estimated to have reserves of natural gas between 8.8 and 10.2 10^{12} m^3 (Council of Canadian Academies, 2008). The proposed development of gas fields in MacKenzie Delta includes two license areas (Fig. 4), which are of a particular concern to Canada Environment:

- Taglu area with a planned production of 8.5×10^{10} m^3 ; and
- Niglintgak area with a planned production of 2.8×10^{10} m^3;

Withdrawal of gas generates a pressure decrease in the reservoir, increased effective stress, which results in a consolidation or compaction of the reservoir material. The Mackenzie Delta gas reservoirs typically consist of layers of coarse porous materials interbeded with layers of fine grained material. The compaction may be elastic or inelastic and is characterized by an elastic or inelastic storage coefficient of the compaction. Ground surface subsidence is a function of the compaction and depth

Fig. 4 License areas and pipeline route of the proposed Mackenzie Gas Project.

of the reservoir, geology, and geomechanical parameters of the overburden and underlying material (Szostak-Chrzanowski et al., 2006).

Boundary and geometry of the productive zone of the reservoir, as well as the amount of the actual compaction are generally difficult to determine. Geology, faulting, and tectonic stresses in the Mackenzie Delta are not well known. The Taglu gas reservoir consists of 5 stacked gas pools in porous sandstones at depths of 2400 – 3200 m below ground surface (Haberle et al., 2004). The Niglintgak subsurface contains a number of hydrocarbon-bearing sands arranged in stacked sand-shale layers (Dudlay et al., 2005). Most of the identified resources are contained in gas-bearing sands, which are buried at a depth of about 900 m.

Theoretically, the gas withdrawal and resulting re-distribution of stresses in the overburden rock mass may activate some locked faults, which could lead to unpredictable consequences. The geomechanical parameters of the reservoir and, particularly, of overburden have to be assumed with a wide range of uncertainty. Uncertainty of deformation parameters of the overburden permafrost adds to the complexity of modeling the prediction of ground subsidence.

The proponents of the development of Taglu and Niglintgak gas fields simulated the expected subsidence process using the finite element method and their own proprietary codes (Haeberle et al., 2004; Haeberle et al., 2005; Dudley et al., 2005). They predicted the following 'most likely' maximum values of the subsidence at the end of 30 years of production:

- 0.38 m at Taglu site and
- 0.45 m at Niglintgak site.

Isolines of the combined predicted subsidence in both fields have been plotted in Figure 5 using the data available in (Haeberle et al., 2004; Haeberle et al., 2005; Dudley et al., 2005).

Due to the uncertainties of geomechanical parameters of the rock material within the reservoirs and in the overburden strata, the predicted values may considerably differ from the actual subsidence values. According to (Chrzanowski and Szostak-Chrzanowski 2010) and (Gale and Konrad, 2006) the above predicted values are too optimistic. The actual subsidence at both fields will be most likely larger. This enforces the need for monitoring of the actual subsidence due to the gas withdrawal during the production period, which is supposed to take between 25-30 years.

4. PRELIMINARY DESIGN OF THE MONITORING SCHEME

4.1. MONITORING REQUIREMENTS

As indicated by the current regional study, the natural ground subsidence of sub-surface (below the effects of active layer of thawing/freezing of permafrost) in the area of the expected effects of gas withdrawal seems to be quite uniform at a rate of – 3.7 mm/year. Therefore, in designing the monitoring scheme, the ground subsidence in Nilintgak and Taglu gas fields will be treated as a local differential deformation with respect to the surrounding area. The monitoring scheme should satisfy the following requirements:

- to give sub-centimetre accuracy of displacements at 95 % confidence level;
- to give three-dimensional information on the ground deformation to be able to separate various causes of deformation;
- to be reliable;
- to be robust to withstand the harsh conditions of the region, and
- must take under consideration the difficult and expensive access to the area either by boat (slow and limited access to some points) or helicopter ($10,000/day) during the short summers, or by using ice roads in the late winter (maintained only till the beginning of April).

4.2. *CHOICE OF TECHNOLOGY*

Various applicable technologies were considered (Chrzanowski and Szostak-Chrzanowski, 2010) including GPS, conventional satellite Interferometric Synthetic Aperture Radar (InSAR), satellite InSAR with corner reflectors (CR-InSAR), aerial laser scanning (LiDAR), geodetic leveling, and array of tiltmeters. It was concluded that use of GPS at discrete points is currently the most reliable and viable method that can satisfy most requirements listed above. GPS alone, however, with the survey monuments anchored several metres below the active layer of permafrost, will not provide information on effects of all causes of ground surface deformation and will not resolve the problem of separation of various causes.

The spatially continuous InSAR would be a good tool for the total surface deformation measurements. Preliminary tests with InSAR were performed in 2008/2009. So far, the results have been negative due to the lack of achieving the temporal coherence between consecutive radar images over periods longer than a few days (Chrzanowski and Szostak-Chrzanowski, 2010). The de-correlation was, perhaps, caused mainly by changes of backscattering properties of the surface of the active layer due to changes in moisture (Zhou et al., 2009). Research will continue on finding the best periods of time (perhaps end of summer) for obtaining the temporal coherence between multiple images collected annually with C-band and X-band InSAR in similar surface and atmospheric conditions.

If InSAR does not give satisfactory results, some other type of simple mechanical or opto-mechanical sensors should be developed and tested to provide the information on the total surface of movements, at least at discrete points, with respect to deeply anchored GPS monuments.

4.3. *RECOMMENDED MONITORING SCHEME*

Based on the evaluation of the various technologies, GPS is recommended to be a core of the monitoring scheme at Niglintgak and Taglu gas fields with a minimum of 25 monitoring points in each field (Fig. 6). The GPS points will be anchored into permafrost by using 63 mm diameter pipes drilled-in to the depth of 15 m. Positions of the monitoring points will be determined with respect to 4-5 local reference points installed beyond the main effects of gas withdrawal. The local reference points will be connected to 3-4 regional control points (Fig. 7) installed in bedrock.

Use of Precision Point Positioning (PPP) method (Bisnath et al., 2009) with the 48 hour observation sessions will be considered. If the problem of temporal coherence in InSAR application would be resolved in the near future, standard InSAR should be added to the monitoring scheme to provide spatially continuous information on the total subsidence of the ground surface. LiDAR (aerial laser scanning) and/or single pass InSAR may play a role in providing a generalized information on the total accumulated surface subsidence, say after 15 years of gas withdrawal, when the subsidence exceeds the accuracy limits (ca. 0.1m) of those techniques.

5. CONCLUSIONS

Complexity of geology and tectonics, degradation of permafrost, post-glacial rebound, and sedimentation loading in Mackenzie Delta pose challenges to the separation of effects of ground subsidence due to the gas withdrawal from natural ground deformation phenomena. Design of geodetic monitoring schemes, besides the accuracy and reliability requirements must consider the harsh conditions of the northern region and difficult and expensive access to the area.

GPS with deep installation of survey monuments in permafrost is considered as the main technology to be used in monitoring ground subsidence due to the gas withdrawal at Mackenzie Delta. If additional tests on obtaining temporal coherence will give positive results, conventional InSAR technology will be added to the monitoring scheme to provide spatially continuous information on the total surface subsidence.

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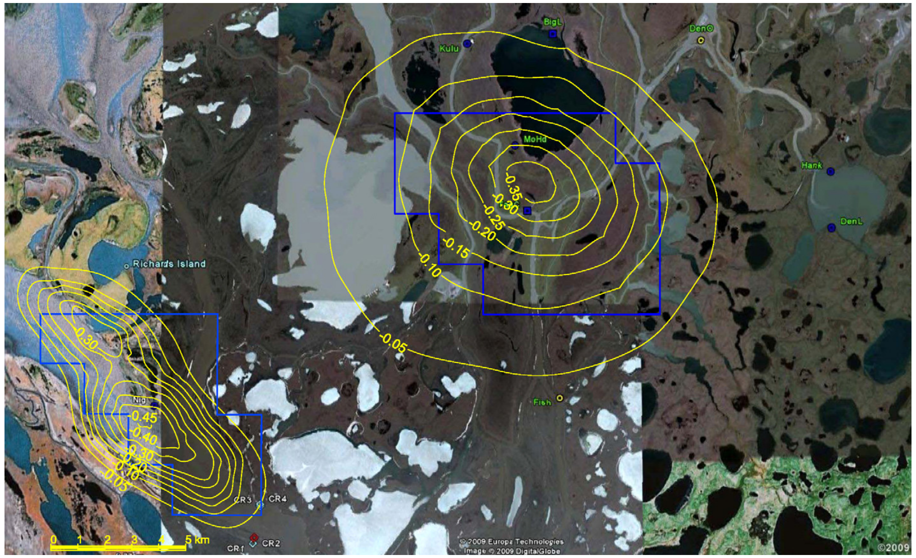

Fig. 5 Isolines of predicted subsidence at Niglingtak and Taglu gas field (based on Haeberle et al., 2005).

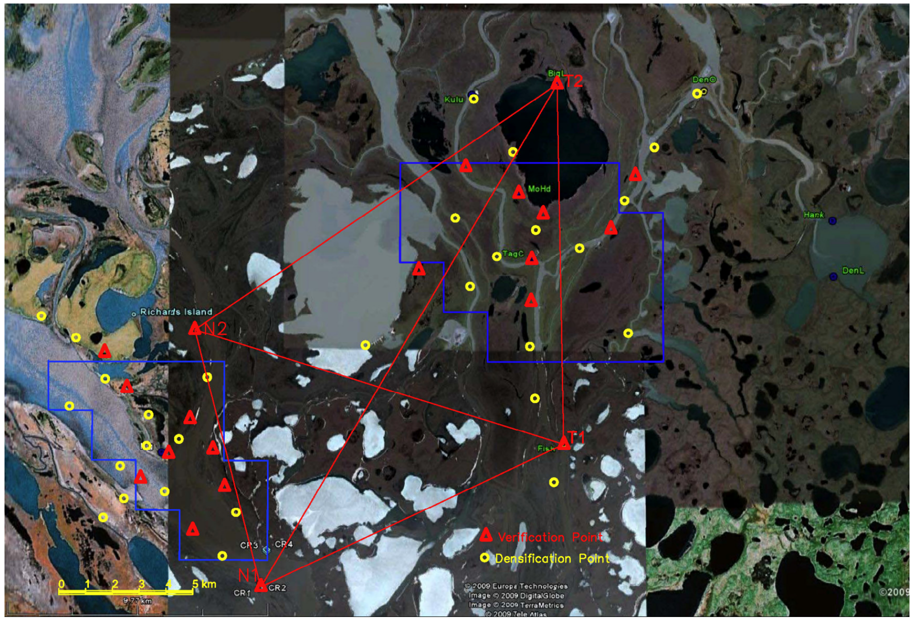

Fig. 6 Proposed GPS Monitoring Network.

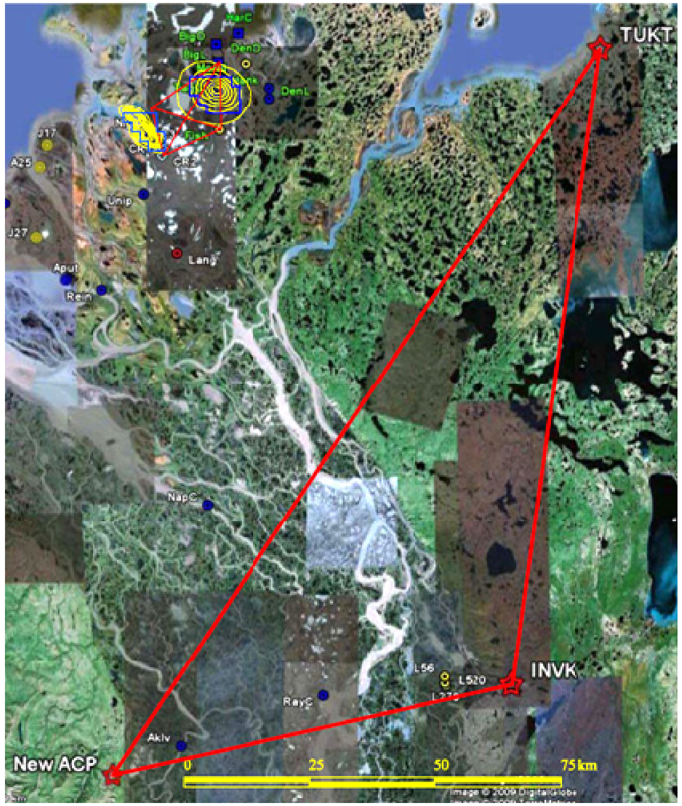

Fig. 7 Regional Active Control Network.