OTC 23733

# Movement Due to Heave and Thaw Settlement of A Full-Scale Test Chilled Gas Pipeline Constructed in Fairbanks Alaska

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This paper was prepared for presentation at the Arctic Technology Conference held in Houston, Texas, USA, 3-5 December 2012.



## Abstract

In this paper the authors report the heave and thaw settlement properties of a test chilled gas pipeline. A full-scale field experiment of the chilled gas pipeline system was conducted in Fairbanks Alaska from 1999 to 2005. The length of the test pipeline was 105m and the diameter was 0.9m. The circulated chilled air was –10 $^{o}$C. One-third of the pipeline was buried in permafrost and the rest of it was placed in non-permafrost. At the end of July 2003, circulation of the chilled air ceased, however, monitoring of the thaw settlement properties of the test pipeline continued until the middle of April, 2005. The results obtained include: 1) As the frost-bulb around the pipeline in non-permafrost section formed, the test pipeline in the non-permafrost section moved upward, resulting in bending of the pipeline at the boundary. 2) In summers, overburden frozen ground of the pipeline became thinner due to the development of active layer above. The pipeline buried in permafrost section moved upward abruptly, fracturing the thinning overburden frozen ground. 3) The phenomenon mentioned 2) occurred successive summer, and the pipeline uplift in permafrost section continued in summers. 4) In relation with 1), the upward movement in non-permafrost section was confirmed by frost heaving of the pipe foundation. 5) Settlement of the test pipeline was also confirmed by thaw settlement of the foundation. 6) During the thawing process, the temperature of the thawing frost bulb became 0 $^{o}$C at first and then thawed rapidly in summer together with the development of active layer. As a result , settlement of the pipeline happened rapidly in summer.

## Introduction

In the existing natural gas production field in permafrost regions such as West Siberia, gas pipelines float in water or are exposed in ditchs as shown in the photos of Fig.1. However the gas pressure at the present time has dropped considerably comparing to the one in the initial production days. This pressure drop enables the damaged pipeline system to survive. However, those initially buried gas pipelines are now mostly exposed and lost the structural stabilities and security reliability.

As for the natural gas pipeline installation in permafrost regions, the buried system has been recommended for security reasons. In order to prevent thawing of the permafrost shown in Fig.1, the gas must be chilled for transportation in permafrost regions. On the other hand, even with the chilled gas pipeline system, miner problems may still happen in limited sections of the pipeline where frost heave damage occurs when the pipeline freezes surrounding soils in non-permafrost section (Talik).

Two primary chilled pipeline test experiments are discussed in the literature: the Calgary Frost Heave Facility and the Caen, France experiment. A third chilled pipeline experiment was conducted at the Fairbanks Frost Heave Facility, but the data remains unavailable to the public. The Caen, France chilled pipeline experiment is well documented in public literature by Geotechnical Science Laboratories (1983, 1986a, 1986b, 1988) and Dallimore and Williams (1985). The purposes of the Caen experiment were to investigate differential heave resulting from the abrupt transition between two different lithologic soils (Caen silt and SNEC sand) with varying frost susceptibilities and the associated stresses incurred by the pipeline and the soil mass. Abrupt lithologic transition zones are common in the natural environment such as the transition between active fluvial gravel deposits and silt overbanks deposits.

a) Washed and exposed pipelines

b) Floating pipeline initially buried in fill

c) Exposed pipeline initially buried in fill

d) Exposed pipeline in a slope

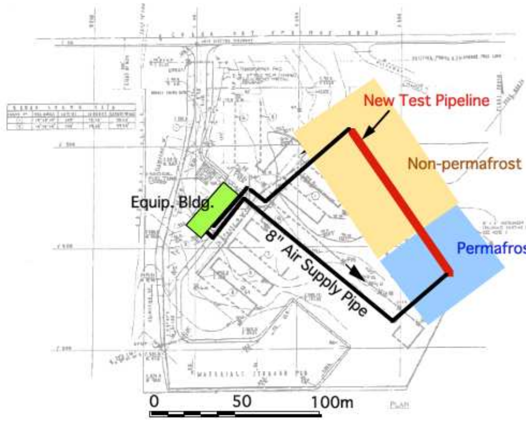
Fig. 1 Situation of existing gas pipelines in West Siberia

The Calgary Frost Heave Experiments, described in detail by Slusarchuk et al. (1978) and Foothills (1981), included six separate test sections with each consisting of 12.2 m long, 1.22-m diameter pipeline. The experiments were conducted under field conditions within a highly frost susceptible thick glacial-lacustrine deposit with an average ground water table between 2.3 m and 2.6 m. In 1974 and 1978, total six sections were constructed.

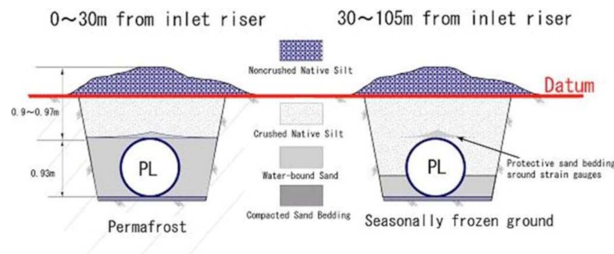
In order to propose a design and construction method for the pipelines in permafrost regions, which prevents these engineering concerns, it is necessary to research the interaction of permafrost and burred chilled pipeline. A full-scale experiment was conducted in Fairbanks, Alaska in order to investigate the behavior of the pipe at the boundary of permafrost and non-permafrost where intense bending moment would be generated and accumulated in the pipe due to frost heaving. Detailed information on this field experiment was presented by Huang et al. (2004).

### Outline of Field Experiment

The field experiment was conducted in discontinuous permafrost area in Fairbanks, Akasla from 1999 to 2005. As for the first step, the depth of permafrost table was sounded with auger borng. A total of 26 boreholes were drilled in order to determine the boundary of permafrst and non-permafrost. Fig.2 a) shows the layout of the test facilities. About one-third of the test gas pipeline was burlied in permafrost and two-thirds in non-permafrost (talik). Total length of the test pipeline was 105m and the pipe specifications are given in Table1. During the freezing phase, the circulating air was chilled by a freezing unit to -10 $^{o}$C. The freezing phase started from December 11, 1999 and ended in July 31, 2003. Then the chilled air circulation was ceased, but monitoring was continued until the middle of April 2005. During the experiment, test pipeline behavior during freezing and thawing phases was monitored.




a) Layout of the test facilities




b) Cross-section of buried test pipeline

c) Welded test gas pipeline right before the lowering

d) A view of the test gas pipeline construction

Fig.2 Layout and cross-sections of the pipeline and photos taken during construction

Table 1 Specifications of test pipe

| | | |
|---|---|---|
| Grade | | API X-65 |
| Material | | Steel |
| Diameter | cm | 91.4 |
| Wall thickness | cm | 0.9 |
| Yield stress | $kg/cm^2$ | 4920 |
| Tensile strength | $kg/cm^2$ | 5760 |
| A (Cross section area) | $cm^2$ | 255.9 |
| I(Geometrical moment of inertia) | $cm^4$ | 261994 |
| E(Young's modulus) | $kg/cm^3$ | 2100000 |
| Z(Modulus of section) | $cm^2$ | 5733 |

**Monitoring Parameters and Methods**

During the experiment (1) wind direction and wind velocity, (2) ground water table (3 wells), (3) temperature (air, pipe and ground temperatures:154 points), (4) ground surface movement right above the pipeline (11points), (5) differential frost heave and thaw settlement above the pipeline (8 points), (6) frost heave and thaw settlement of the 1m thick soil layer beneath the pipeline (5 points), (7) vertical displacement of pipeline (28 points), and (8) strain at pipe surface (40 points) were monitored.

In the following sections the major monitoring parameters are described.

***Temperature***

Thermal regime of the test pipeline and surrounding ground was monitored with 154 thermistors. One was for air temperature, neine were for test pipeline temperature, and 144 were for ground temperature monitoring. Thermistor strings were placed to form three "thermal fences" as shown in Fig.3. Thermal fence A (TFA), thermal fence B (TFB) and thermal frnmce C (TFC) were placed 58m, 36.5m, and 13m from the air inlet riser, respectively. The depth of each of the thermistors is schematically shown in the figure.

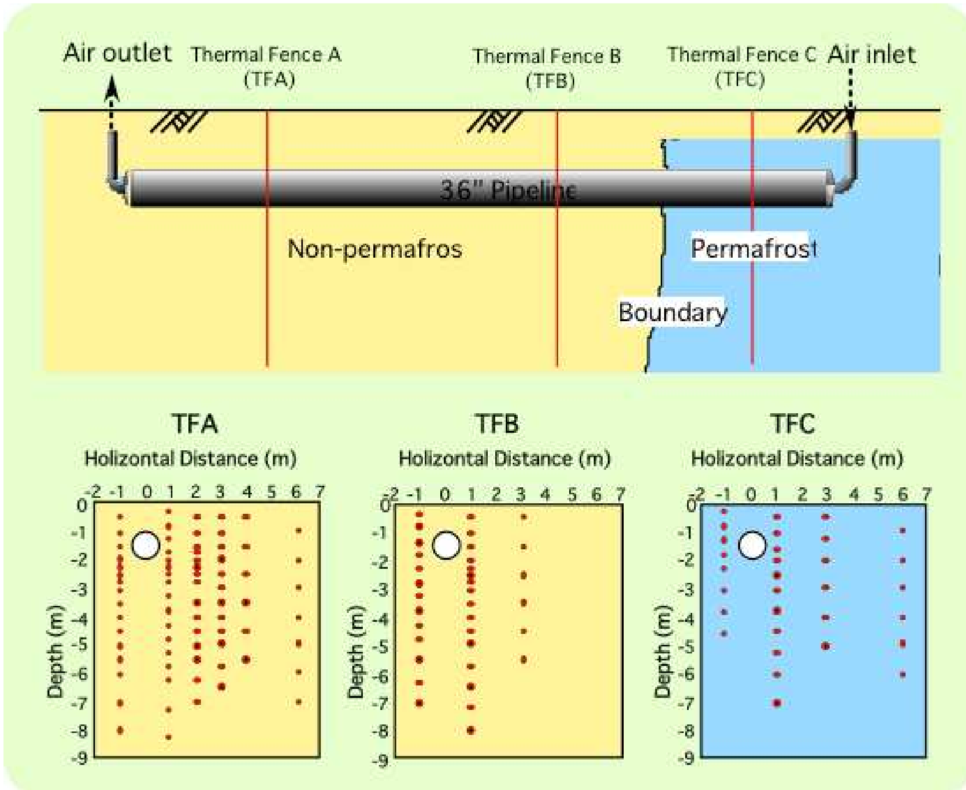



Fig.3 Location of thermistors

***Pipe Movement***

Vertical movement profile of the test pipeline is the most important information to be obtained in this experiment. Heave rod method, which is simple and reliable, was utilized. Heave rods were welded at the locations shown in Fig.4. Fig.5 a) shows the view of welded steel rod at the base and b) shows the view of plastic casings, which enclosed heave rods.

Pipe vertical movement was monitored by measuring the level of upper tips of heave rods by leveling survey. The leveling survey was conducted mostly every other week.

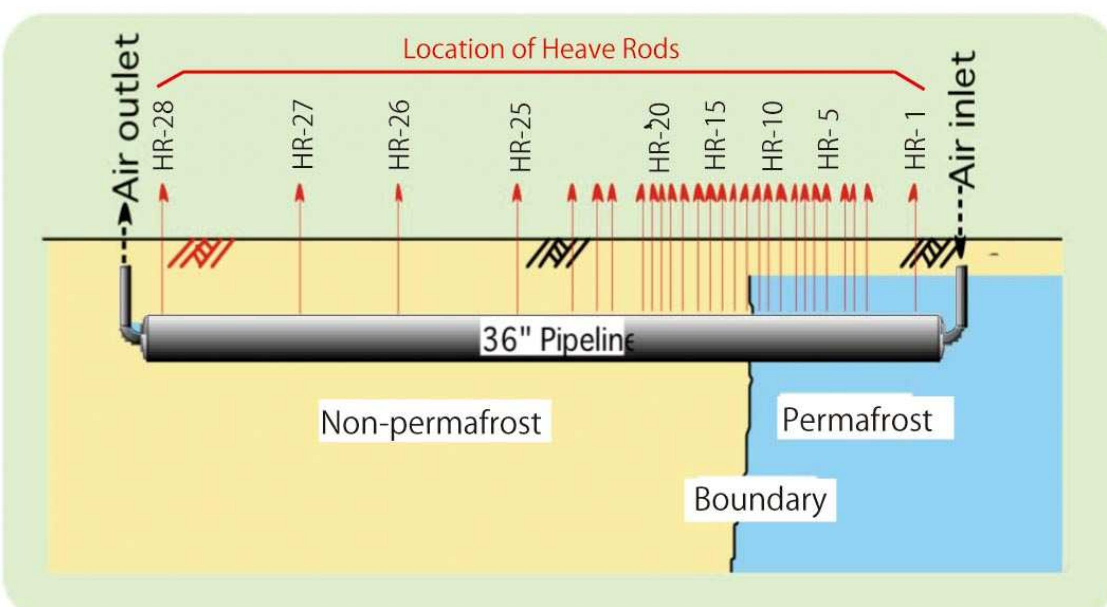



Fig.4 Location of heave rods

a) Welded rod at the base

b) Plastic casings enclosing heave rods

Fig.5 Heave Rod installation and construction

***Soil Heave and Thaw Settlement in Pipe Foundation***

The vertical movement of test pipeline should be due to frost heaveing of the pipe foundation. Five LVDTs were installed in the foundation as shown in Fig.6. Each of the five water proofed LVDTs had an anchor plate at the top and a dead weight at the lower end of the rod as shown in Fig. 6 (right). In that the anchor plate and the bottom of the dead weight define the target soil layer for monitoring. Monitored value of the LVDT shows the heave or settlement of the target layer.

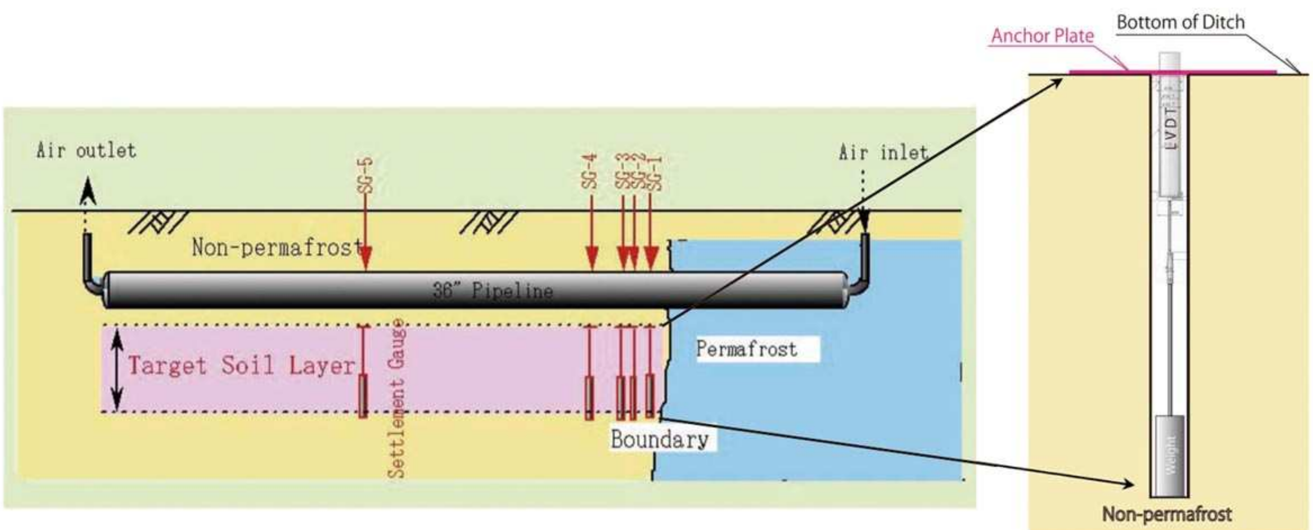



Fig.6 Locations of LVDTs in pipe foundation

***Pipe Strain***

Since the test pipeline was buried about 30% in permafrost and 70% in non-permafrost (talik), the pipeline might bend in the vicinity of the boundary when circulation of the chilled air started .

In order to monitor the stress condition of pipeline in the vicinity of the boundary, fourty water proofed strain gauges were welded to the pipe outer surface (see Fig.7). Each location of the strain gauge installation is shown in Fig.8 with a red arrow, and stranin gauges were welded in the one of the configurations shown in Fig.8 (right).

Fig.7 Welded strain gauge

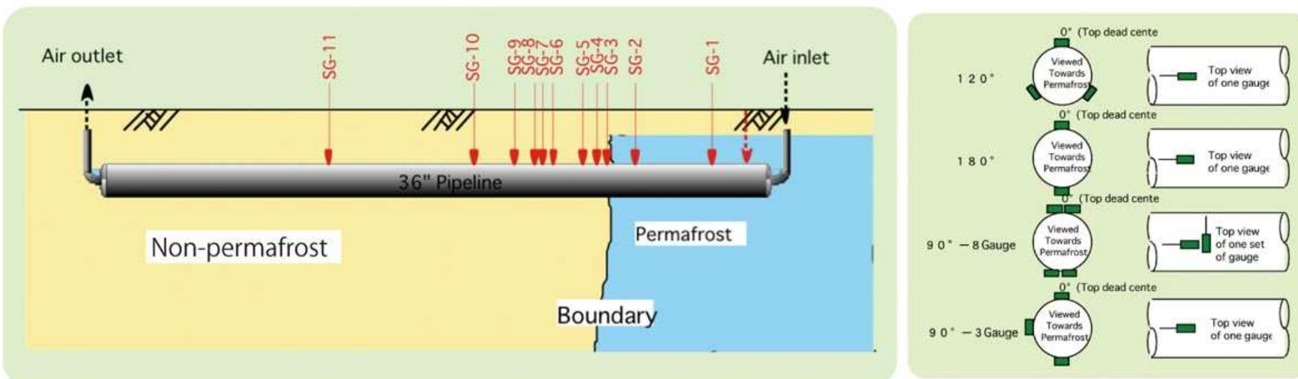



Fig.8 Locations and configurations of the strain gauges

## Test Results and Discussions

In this paper some of the data acquired during experiment such as thermal regime of the test site, vertical movement of the test pipeline and correlation between test pipe movement and foundation deformation are demonstrated and discussed.

### Thermal Regime

As was mentioned earlier the three thermal fenceses, such as TFA, TFB and TFC, were prepared for monitoring thermal regime of the experimental site. In the following, the data obtained at TFA is shown because TAF was well away from the boundary so that the data was considered as the typical thermal condition around chilled gas pipeline in a freezing talik zone.

The temperature data of TFA were interpolated using Kernel Smoothig to 2D image. The 2D temperature profile images of mid March and mid September of 2000 to 2005 are shown in Fig. 9.

The experiment started on December 11, 1999. Frost bulb, which grew around the chilled gas pipeline was consistently enlarging at least until September 15, 2003. The circulation of chilled air ceased on July 31, 2003, and the temperature of frost bulb seemed to reach the soil freezing temperature in a few months. Then by the following summer as the thawing taking place, the frost bulb was gone.

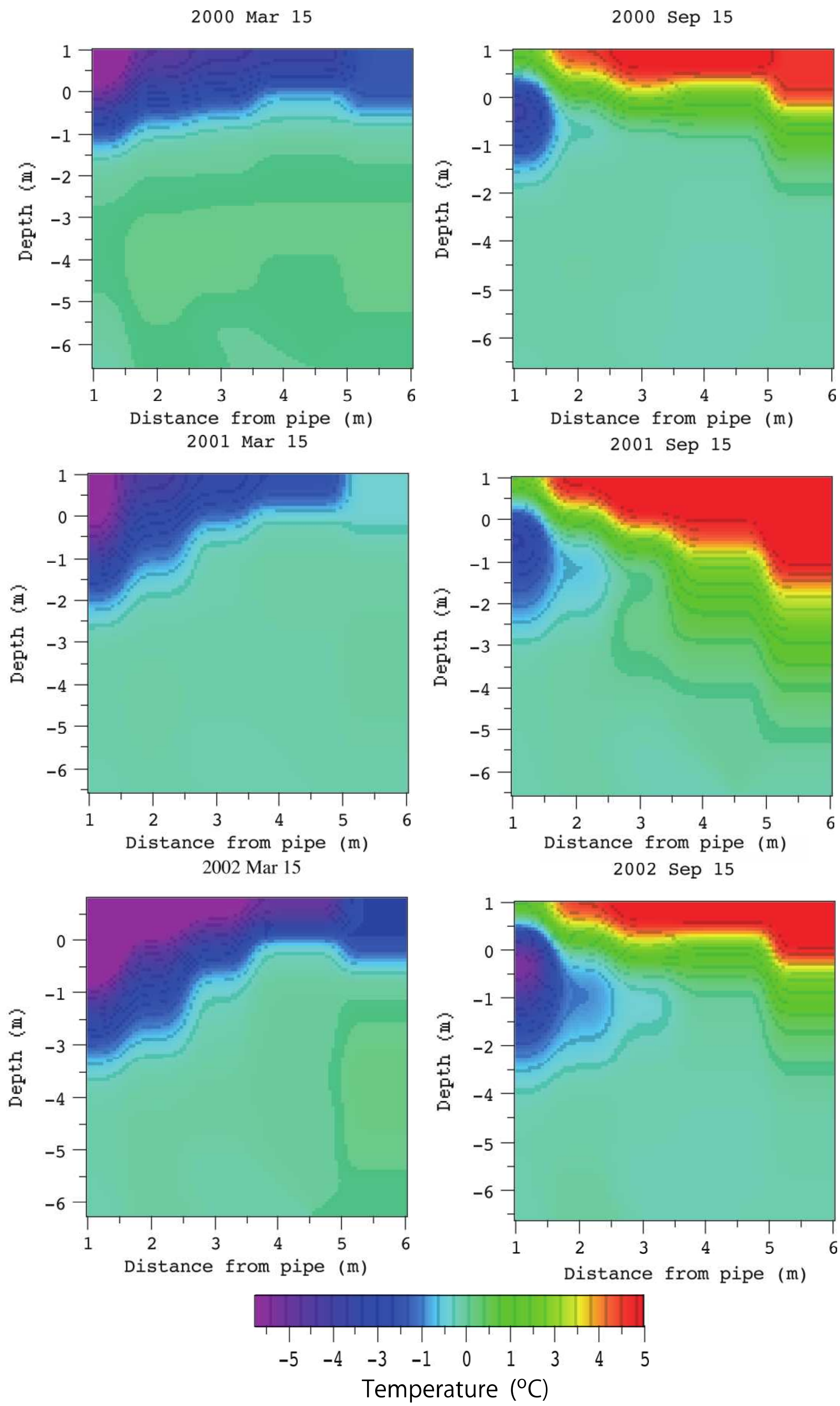



Fig.9 Thermal regimue of TFA

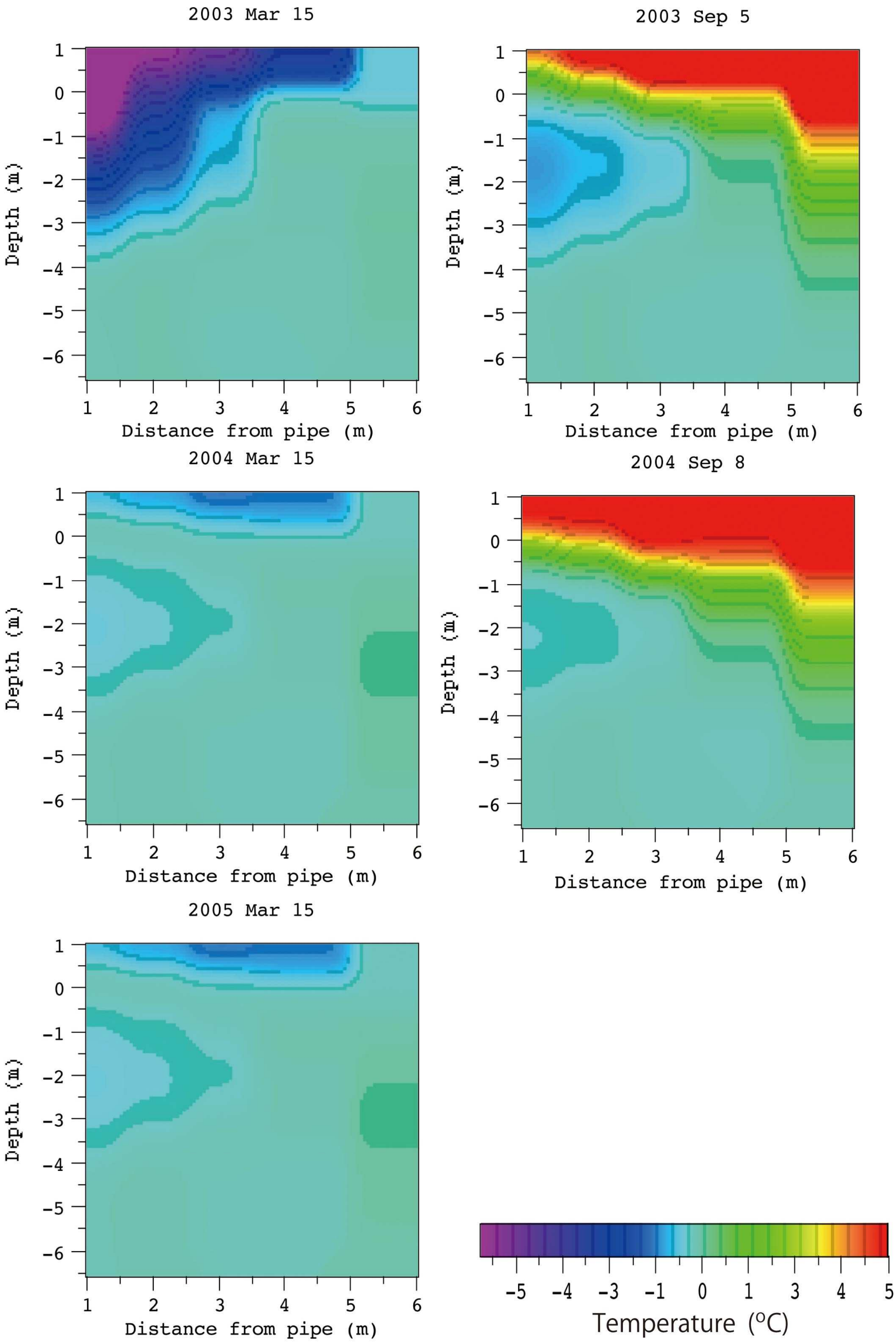



Fig.9 Thermal regimue of TFA (Conteniued)

**Pipe Movement**

Relative elevation difference of heave rod tip from the elevation of December 11, 1999 is defined as the vertical movement of pipeline. All the vertical movements of heave rods were calculated in the certain time interval and the result is shown in Fig.10 togethor with temperatures of the pipeline (right).

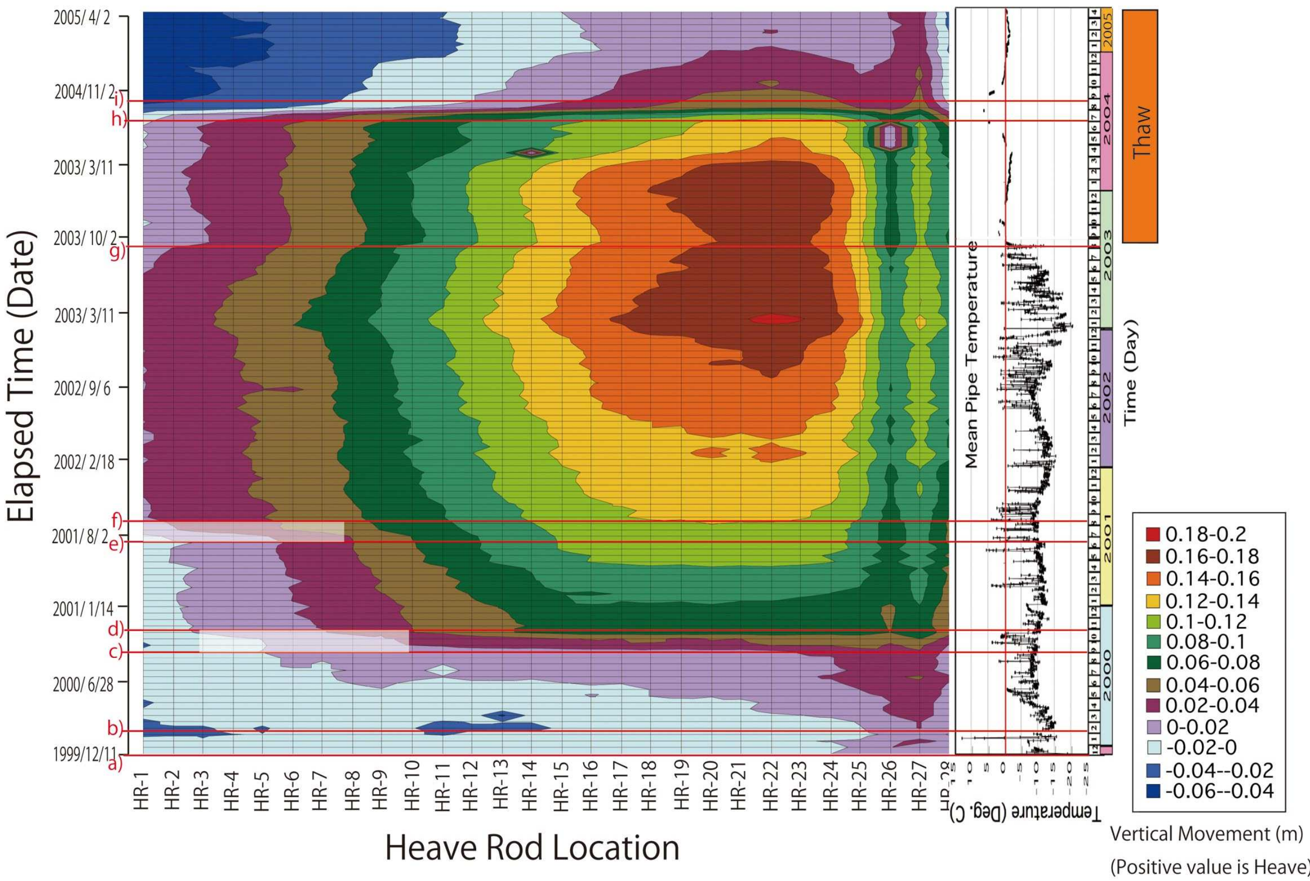



Fig.10 Vertical movement of test pipeline in freezing and thawing phases

In the first 2 month, i.e. a) to b) marked on the time scale in Fig.10, most portion of the pipeline had settled except the pipeline section from HR-25 to HR-28. Then from b) to c) upward movement took place in non-permafrost (talik) section. During the late summer to early winter of 2000, i.e. c) to d), rather abrupt uplift was observed in the secton between HR-3 to HR-10, i.e. marked semi transparent white bar. From d) to e) rather active vertical uplift was observed in the pipeline section between HR-9 and HR-24. From e) to f) rather abrupt uplift was observed again in the secton between HR-1 and HR-8, i.e. marked semi transparent white bar. From f) to g) rather active vertical uplift was observed in the section from HR-18 to HR-24. Chilled air circulation was ceased at g), and the pipe temperature became almost 0 $^{o}$C in a very short time. However, the elevation of pipeline was at the same level for eight month and then started subsidence in non-permafrost section between HR-17 and HR-24. In the summer of 2004, i.e. h) to i), sudden subsidence took place almost to the initial grand level.

The seqence of the pipeline bending and abrupt pipeline uplift in permafrost section are assumed as:

1) Frost bulb grows around the pipeline which passes through talik (blue lines in Fig.11);
2) Frost heave takes place during the frost bulb growth;
3) Pipeline in talik is pushed up as the red arrow in Fig.11 indicates, whereas pipeline in frozen ground is fixed within frozen section, i.e. “Condition 1” shown in Fig.11 (correspond b) to c), d) to; e) and f) to g) in Fig.10);
4) During “Condition 1” pipeline in frozen overburden is trying to push up the frozen overburden layer, i.e. green arrow in Fig.11;
5) Overburden ground layer thaws in summer and the confining stress drops, i.e. “Condition 2”;
6) When the confining stress becomes lower than the upward push force as indicated by green arrow, the pipeline in the section forces the oververden frozen layer to move up as shown as “Condition 3” (correspond c) to d), and e) to f) in Fig.10);
7) These steps repeat while “Condition 1” is consistently satisfied.

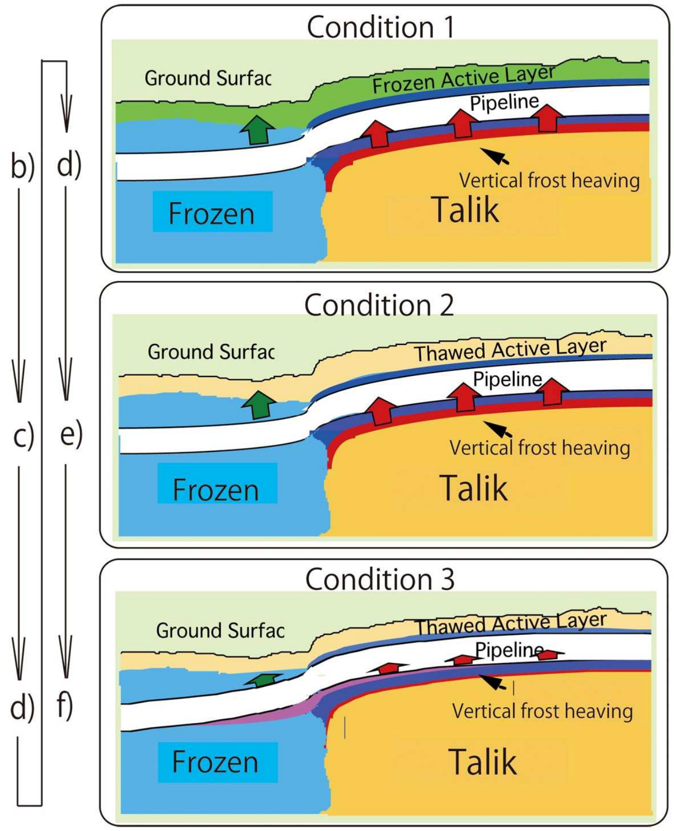



Fig.11 A proposing sequence of ablapt pipeline uplift

**Soil Settlement at Pipe Foundation during Thawing Stage**

In Fig.12, data acquired from LVDT of HG-5, which was demonstrated in Fig.6 and pipeline vertical movement monitored with HR-26 are shown.

As was mentioned in the section of the thermal regime, ground temperature around the pipeline approached freezing point shortly after the chilled air circulation was ceased. And then in the second summer the $0^{o}$C frozen soil thawed and became $0^{o}$C unfrozen ground. Since unfrozen soil had far less bearing capacity than in the frozen state, severe subsidence could happen.

The LVDT read-out showed that after the cessation of circulation no heave expansion and thaw settlement had happened in the days from 1380 to 1640. However the same amount of pipe subsidence was monitored as the pipe foundation settlement in the second summer after the circuration ceased, i.e. the days from 1640 to 1740.

Therefore it is rational to postulate that the pipeline settled due to the thaw settlement of the 1m thick foundation layer during the period.

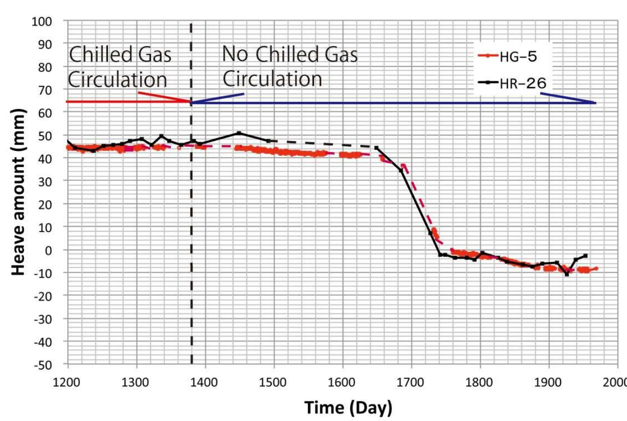



Fig.12 Vertival pipe movement and foundation Settlement during thawing

## Summary of Conclusions

1) If pipeline operating with chilled gas pipeline system in permafrt regions passing through talik, frost bulb grows around pipeline, and if the soil is frost susceptible, the pipeline may move up due to frost heaving.
2) As is recognaized, if the condition mentioned in 1) is met, clear bending will occur at the boundary of permafrost (frozen) and non-permafrost (Talik), (this is demonstrated at "Condition 1" in Fig.11).
3) A new phenomenon is found that the condition mentioned in 2) is fulfilled descending of permafrost table will trigger the abrupt pipeline uplift in the permafrost side of the boundary, (this is demonstrated in "Condition 2" and Condition 3" in Fig.11.
4) The sudden uplift mentioned in 3) may continue in the consecutive summer and early winter.
5) After the operation of chilled gas pipeline system ceases, temperature of frost bulb changes to 0 $^{o}$C in a few month.
6) And then the frozen 0 $^{o}$C ground changes its property to 0 $^{o}$C unfrozen ground in one summer.
7) Owing to the phenomenon mentioned in 6), sudden subsidence of pipeline may occur.
8) If the frost bulb has high ice content, thawed 0 $^{o}$C foundation becomes slurry and the pipe will be floated by the buoyancy.

## Acknowedge

This experiment was sponsored by the Japan Science and Technology Agency. Authors would like to thank Dr. Matthew T. Bray and Dr. Margaret M. Darrow for their help with the field activities.

## References

1. Geotechnical Science Laboratories. 1983. Investigation of soil freezing in association with a buried chilled pipeline in a large-scale test facility, phase 2. 41 pp.
2. --------- 1986a. Thermodynamcis and Mechanics of Freezing Soil Around a Pipeline. Report to Energy, Mines and Resources, Canada, Earth Physics Branch, 111 pp.
3. --------- 1986b. Investigations of Frost Heave as a Cause of Pipeline Deformation. Report to Energy, Mines and Resources, Canada, Earth Physics Branch, 70 pp.
4. --------- 1988. Canada-France Ground Freezing Experiment: Phase VII: Spatial Variability of Heave Around a Pipeline and the Effects of Repeated Freezing and Thawing. Report to Energy, Mines, and Resources, Canada, Permafrost Section, Terrain Science Division, Geological Survey of Canada, 34 pp.
5. Dallimore, S.R., and Williams, P.J., eds. 1985. Pipelines and Frost Heave: Proceedings of a Seminar at Caen, France, April 25-27, 1984. Carleton University, Ottawa, Canada, 75 pp.
6. Slusarchuk, W. A, et. al. 1978. Field test results of a chilled pipeline buried in unfrozen ground. International Conference on Permafrost, Proceedings No. 3, p 877-883.
7. Foothill Pipe Lines (South Yukon) Ltd. 1981. Plans for dealing with frost-heave and thaw settlement: Addendum to the Environmental impact statement for the Yukon section of the Alaska Highway Gas Pipeline. Calgary, Alberta, p. 1-46.
8. Scott L. Huang, Mathew Y. Bray, Satoshi Akagawa and Masami Fukuda, 2004. Field Investigation of Soil Heave by a Large Diameter Chilled Gas Pipelinde Experiment, Fairbanks, Alaska, J. Cold Regions Engineering, ASCE, pp.2-34, 2004. 3