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Countermeasures for Bending and Abrupt Uplift of A Full-scale Test Chilled Gas Pipeline Observed at Boundary between Frozen Ground and Talik

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Abstract

In this paper the authors report the vertical bending properties of a test chilled gas pipeline and the countermeasures of the bending. 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 frozen ground and the rest of it was placed in talik. At the end of July 2003, circulation of the chilled air ceased, however, monitoring of the thaw settlement-related properties of the test pipeline continued until the middle of April 2005. The following results were presented at the 2nd ATC: 1) As the frost-bulb around the pipeline in talik section formed, the test pipeline in the talik section moved upward, resulting in bending of the pipeline at the boundary. 2) In summers, frozen overburden soil of the pipeline became thinner due to thawing of active layer above. The pipeline buried in frozen section moved upward abruptly, fracturing the thinning frozen overburden ground. 3) The phenomenon mentioned in 2) occurred in successive summers, and the pipeline uplift in frozensection continued. 4) In relation with 1), the upward movement in talik section was confirmed by frost heaving of the pipe foundation. In this report the bending behavior of the test pipeline is described and the several methods to deal with the bending are proposed.

Introduction

In the existing natural gas production fields in permafrost regions such as West Siberia, segments of gas pipelines could become floating in water or exposed in ditches. The inline gas pressure at the time of events might have dropped considerably from the initial production pressure. This pressure drop had enabled the damaged pipeline system to survive. As time progressed, many of those initially buried gas pipelines became 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 permafrost, the gas must be chilled for transportation in permafrost regions. On the other hand, even with the chilled gas pipeline system, minor problems can still happen in limited sections of the pipeline where frost heave damage occurs as the pipeline freezes surrounding soils in talik.

Two primary chilled pipeline test experiments are discussed in 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.

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 pipe. The experiments were conducted under field conditions within a highly frost susceptible thick glacial-lacustrine deposit with an average ground water table between 2.3m and 2.6m. In 1974 and 1978, total six sections were constructed.

In order to propose a design method for pipelines construction in permafrost regions, which prevents the frost heave related 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 talik 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 near Fairbanks, Alaska from 1999 to 2005. As for the first step, the depth of permafrost table was determined with auger boring. A total of 26 boreholes were drilled in order to determine the boundary of permafrost and talik. Fig.1 shows the result of the sounding. About one-third of the test gas pipeline was buried in frozen ground and two-thirds in talik. Total length of the test pipeline was 105m and the pipe steel was API X-65. 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 on July 31, 2003. Then the chilled air circulation was ceased, but monitoring was continued until middle of April 2005. During the experiment, test pipeline behavior during freezing and thawing phases was monitored.

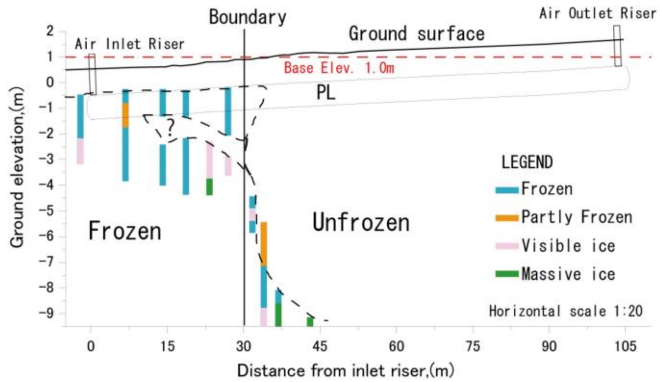


Fig.1 Vertical permafrost distribution along test pipeline

During the experiment (1) wind direction and wind velocity, (2) ground water table (3 wells), (3) temperature (air, pipe and ground temperatures at154 points), (4) ground surface movement right above the pipeline (11 points), (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 at 11 gauge stations) were monitored. Detailed monitoring parameters and methods are discussed in Akagawa et al. (2012). In this section the method to monitor the vertical displacement of the test pipeline and heave and thaw settlement in pipe foundation is described.

Pipe Movement Monitoring Method

Profile of the test pipeline vertical movement was 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.2.

Pipe vertical movement was monitored by measuring the level of upper tips of heave rods by leveling survey. The leveling survey was conducted once every two weeks.

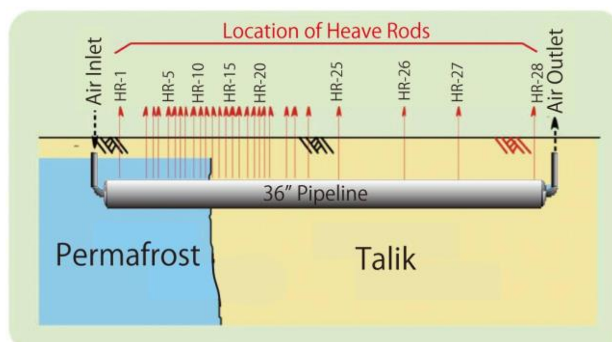


Fig.2 Location of heave rods

Soil Heave and Thaw Settlement in Pipe Foundation

The vertical movement of test pipeline was due to frost heaving of the pipe foundation. Five LVDTs were installed in the foundation soil as shown in Fig.3. 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. 3 (right). In that the anchor plate and the bottom of the dead weight define the target soil layer for monitoring. Measurements of the LVDTs showed the heave or settlement of the target layers.

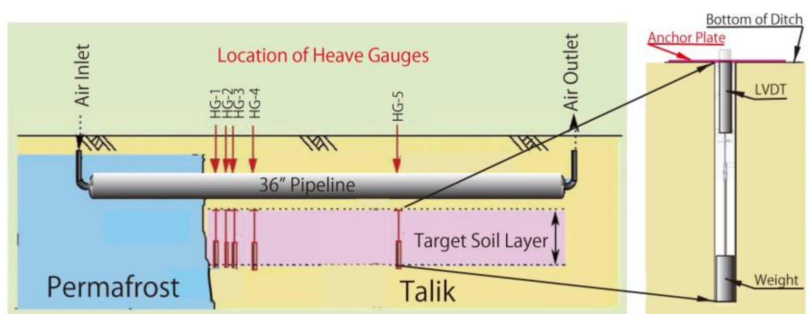


Fig.3 Location of heave gauges

Pipeline Movement

Vertical elevation profiles of the test pipeline in each two-week period throughout the freezing phase of the experiment are plotted in Fig.4. The profiles show relative movement from the initial elevation measurement on December 11, 1999. Since the relative elevation profiles at HR-26 (74m) and beyond show a different trend, due in part to their locations outside of the frost-heave induced bending zone, this report will discuss events observed between 0 to 60m from the air inlet riser.

Vertical elevation profiles show the following six phases, which indicate different test pipeline moving patterns;

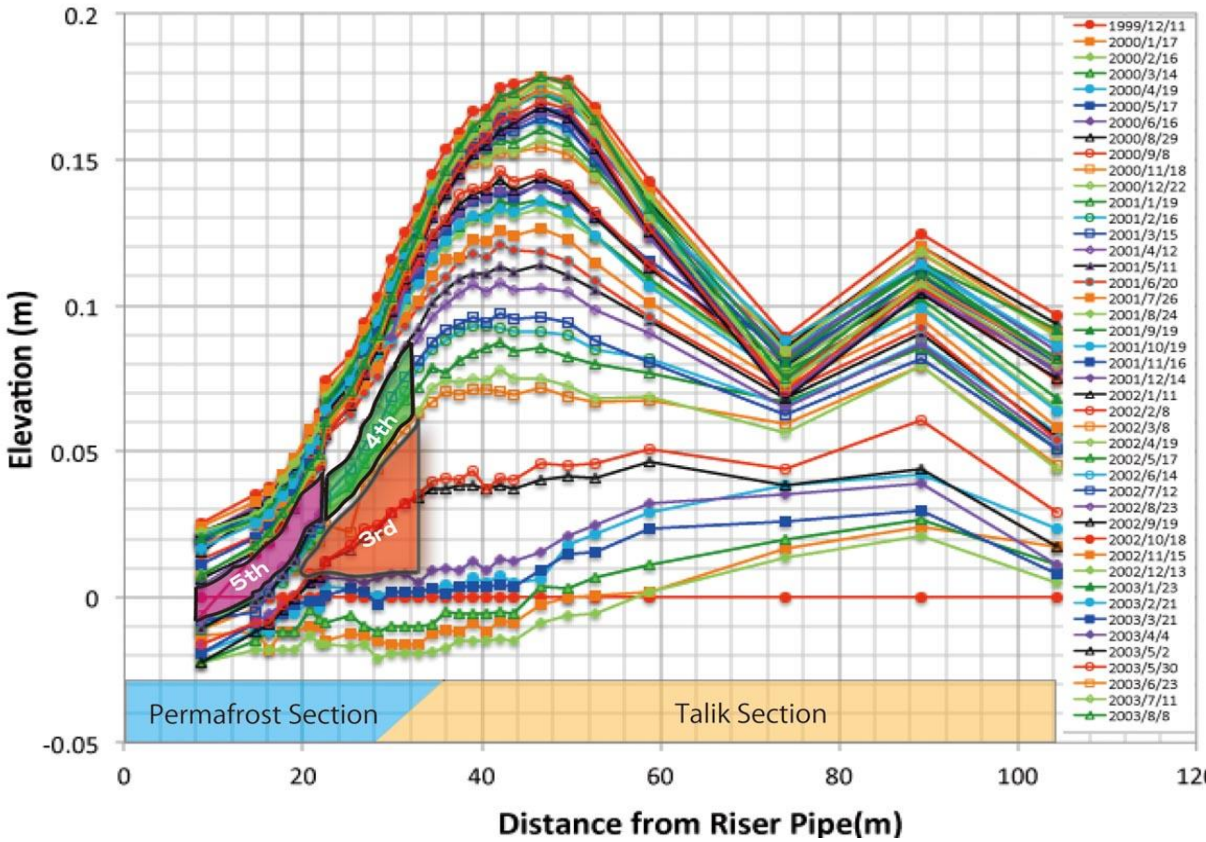


Fig.4 Vertical elevation profiles of the test pipeline

First Phase: From the begining of chilled air circulation to mid February of 2000, the segment of test pipeline between 0 and 40m from the air inlet riser settled about 2cm whereas the rest of the pipeline in talik section moved upward. This is seen in Fig.5a) which shows the vertical relative movent profile obtained by subtracting each heave rod elevation at the first day of the phase from the corresponding heave rod elevation at the last day of the phase. The maximum elevation difference during this period was about 4cm.

Second Phase: From mid February of 2000 to mid June of 2000, the test pipeline moved up about 3cm from 15m and farther as shown in Fig.5b). However the pipeline in 0 to 15m did not move up as much as farther section.. This event is shown in Fig.5 b).

Third Phase: From mid June of 2000 to mid November of 2000, the test pipeline in talik section moved up about 6cm whereas the pipeline in 0 to 15m consistently moved much less than the section in talik as shown in Fig.5c). As the result, the pipeline in the frozen section of 22 to 32m showed the pipeline section where the pipe was bent in this phase. This event is seen in the orange colored triangle in Fig.4 and light blue rectangle in Fig.5 c).

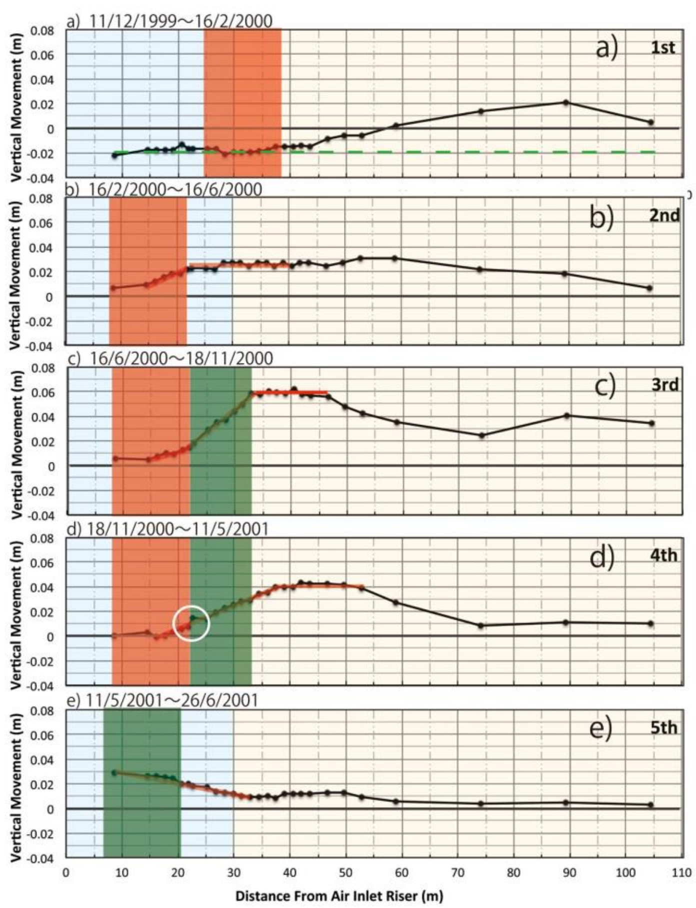
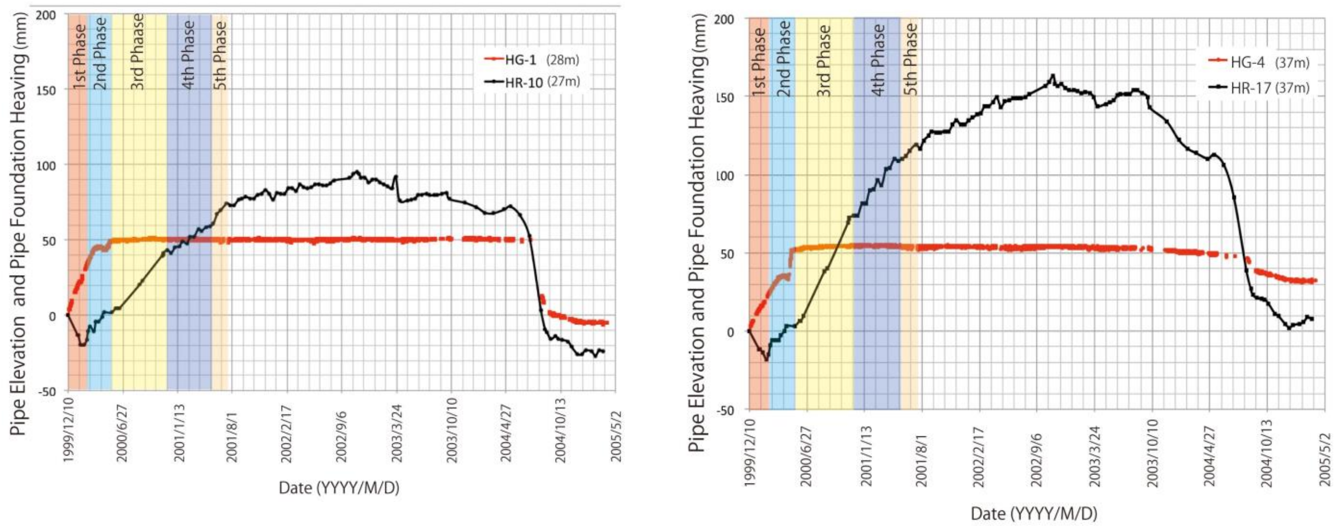


Fig.5 Relative vertical Pipline movement profile during each phases



a) frozen section b) talik section

Fig.6 Pipeline elevation and pipe foundation heaving in frozen section and talik section

Fourth Phase: From mid November of 2000 to mid May of 2001, the test pipeline in talik section moved up about 4cm whereas the pipeline in 0 to 15m hardly moved as shown in Fig.5d). As the result, the pipeline in the frozen section of 22 to 32m showed the pipeline section where the pipe was bent during this phase. It is noteworthy that the test pipeline at around 22m moved up rapidly as is seen at 22m in Fig.5 d). This event corresponded to the green colored area in Fig.4.

Fifth Phase: From mid May of 2001 to mid June of 2001, the test pipeline in frozen section of 0 to 22m moved up about 3cm whereas the pipeline in talik from 30m and farther did not move as shown in Fig.5e). As the result, developed bending shape of near the boundary of frozen section and talik section was relaxed. This event corresponded to the pink colored area in Fig.4

Sixth Phase: After mid June of 2001 the confinement condition of the pipeline in frozen section was unclear due to the pipeline behavour in the previous phase. Therefore data after this date is not delt with in this report.

Process of Pipeline Movement

First Phase: As was demonstrated above the test pipeline buried in 0 to 40m from the air inlet riser firstly settled then moved up. According to the data shown in Fig.6, the turning point was found to be mid February of 2000. The vertical movement of pipeline measured at HR-10 and HR-17 which were installed at 27 and 37m, respectively, and data obtained with pipeline foundation forst heave gauges i.e. HG-1 and HG-4 which were installed at the same locations of HR-10 and HR-17 are shown in Fig.6. The figure shows that the test pipeline at the location of HR-10 and HR-17 moved downward until early February 2000, whereas the foundation ground upheaved by frost heaving constantly until the end of March 2000. The lowing of the pipeline is thought to be due to the settlement of backfilled material. Because the chilled air circulation was started about one month after the completion of pipeline backfilling, backfilled chunks of native frozen soil had not been stabilized yet. This settlement was noted to happen not only in frozen section but also in talik section. However, the test pipeline in talik sesstion did not have much settlement as frozen section. This happened because the amount of frost heaving in talik section was greater than the settlent mentioned above. As the result, the test pipeline was bent at the interface of the frozen section and talik section in this early stage of the experiment. According to the numerical analysis, which has simulated this field experiment, revealed the bending stress profile along the bottom of the test pipeline (i.e. red line) as shown in Fig.7 (Kanie et al., 2006). The bending stress profile indicates that the frost heave caused by frost bulb growth pushed up the test pipeline in talik section and the confinement by the frozen overburden layer above the test pipeline in permafrost section hold back the test pipeline as shown in Fig.7. The location of the confinement corresponds to the area shown in Fig.5 a) with pale reddish box. This confinement is activated as the counterforce of the bending stress in permafrost section shown in Fig.7.

Second Phase: After the settlement ceased, the test pipeline started to move up with about the same rate as frost heaving in foundation soil as shown in Fig.6 a) and b). The pipeline upheaval observed in this phase and in the section where HG-1 and HG-4 were installed, were found to be caused by frost heaving of pipeline foundation. On the other hand, static behavior of the test pipeline in 0 to 15m suggests that the pipeline in this section was firmly confined with frozen ground.

Third Phase: In this phase, frost bulb has grown much deeper than the bottom of the target soil layer of HG-1 and HG-4, no expansion or shrinkage of the layer was measured until frost bulb became smaller due to cessation of the chilled air circulation in April 2005 as shown in Fig.6. However, Fig.6 a) and b) show a clear and rather steep increase of pipeline elevation in frozen and talik sections. This means that the test pipeline buried in frozen soil section of 27m in length moved up together with the pipeline buried in unfrozen soil section of 37m. Considering the trend and the difference of the upheaval amount of HR-10 and HR-17 in this phase, it is clear that the frozen layer which confined the test pipeline of 22 to 32m from the air inlet riser, was separated from the permafrost body underneath. This separation could have been caused by the bending stress in permafrost section. Due to the bending of the test pipeline, which was initiated during the first phase, bending stress in permafrost section was developed in the frozen section and its location is shown with pale reddish zone in Fig.5 a). and b). This stress overcomed the confining strength of the frozen ground in summer when thaw depth of active layer became thicker, then the separation mentioned above commenced. As the result, the location of peak bending stress in permafrost section must have moved to the section somewhere about 7 to 22m from the air inlet riser and is shown in Fig.5c) with pale reddish box

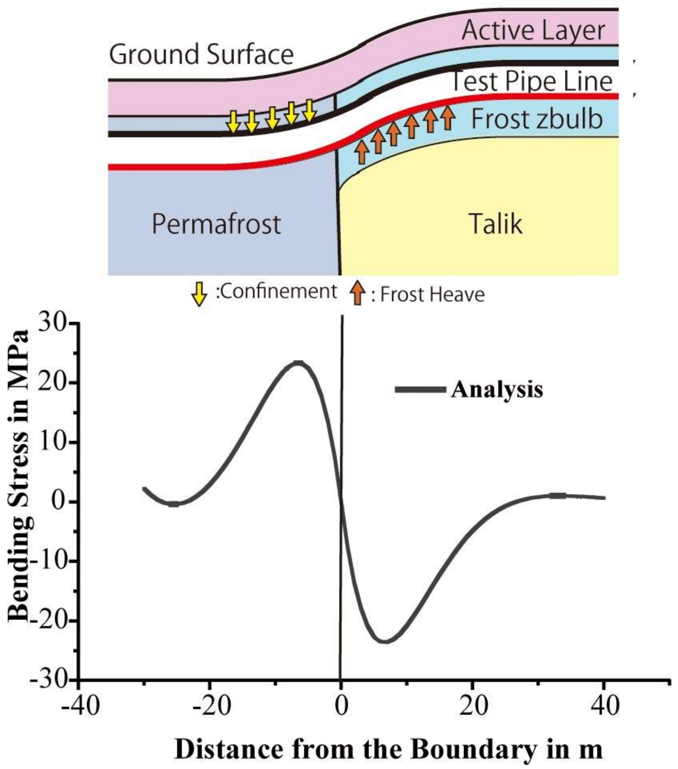
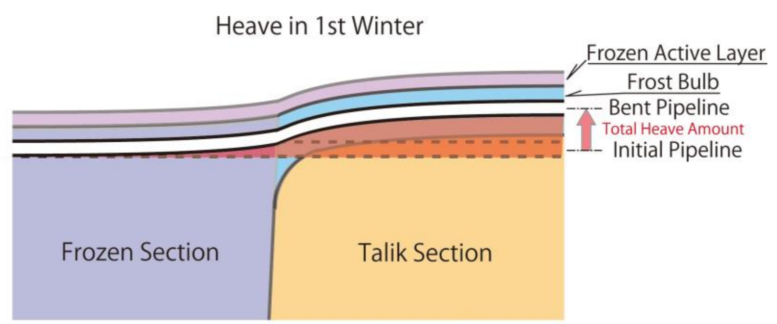


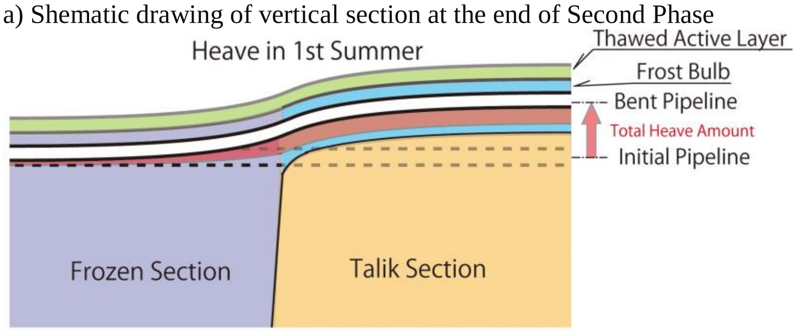
Fig.7 Bending stress developed at the boundary of frozen section and talik section

Forth Phase: Since the upheaval of HR10 was smaller than that of HR-17 in this phase, the bending stress in permafrost section shown in Fig.7 was developed in the test pipeline of 15 to 25m from the air inlet riser. At the end of this phase, this stress separated the frozen layer, which confined the test pipeline of about 22m from the permafrost body underneath again.



a) Shematic drawing of vertical section at the end of Second Phase

Fifth Phase: Due to the breakage at the end of the fourth phase, the positive bending stress in permafrost section shown in Fig.7 moved to 10 to 15m from the air inlet riser (i.e. -15 to -20m from the boundary). Then the same breakage took place in the section and the initial confinement in the permafrost section totally vanished. The test pipeline started to move keeping the same elevation profile after this phase.



b) Shematic drawing of the vertival section at the end of Third Phase
Fig.8 Shematic drawing of the vertival section along test pipeline

Countermeasures for Pipeline Bending and Abrupt Uplift

Countermeasures for Pipeline Bending Observed in the First Phase

According to the field experiment described, following countermeasures are recommended;

If the soil in the talik where chilled gas pipeline is to be constructed has high frost heave susceptibility, frost heaving of pipeline foundation may take place and the pipeline will be pushed up in the talik section. This will develop bending stress in pipeline at the boundary of frozen section and talik section in discontinuous permafrost regions. In order to minimize the future engineering issues, following countermeasures are suggested;

1) Replacing native soil with NSF soil at the boundary (dimension of replacement needs to be designed);
2) Utilizing flexible pipe for reducing bending stress (certain flexible pipes have to be developed); and
3) Utilizing rigid pipe for withstanding the bending.

Countermeasure for Abrupt Uplift Observed in the Third to Fifth Phases

As was mentioned in Fig.7, bending stress develops when pipeline is bent at the boundary. The bending stress may cause problems mentioned above. In order to minimize the future engineering problems, following countermeasures are recommended;

1) Replacing native soil with NSF soil at the boundary (dimension of replacement needs to be designed);
2) Placing pipeline at a greater depth than customary design to increase confinement in frozen section; and
3) Utilizing flexible pipe for reducing bending stress (certain flexible pipes have to be developed).

Universal Countermeasure

As is mentioned in this report, the pipeline bending may cause abrupt uplifting due to the positive bending stress shown in Fig.7. Therefore the countermeasures mentioned above will be effective to both of them;

1) Replacing native soil with NSF soil at the boundary (dimension of replacement has to be designed); and
2) Utilizing flexible pipe for reducing bending stress (certain flexible pipe has to be developed).

Summary of Conclusions

1) At the boundary of frozen ground and talik in permafrost regions, chilled gas pipeline is bent along with the frost bulb growth in the ground that talik is consisted of frost susceptible soil.
2) The pipeline mentioned above has to be durable against the bending stress developped.
3) In order to minimize the engineering concerns, following countermeasures are considered effective:
   a) Replacing native soil with NSF soil at the boundary (dimension of replacement has to be designed)
   b) Utilizing flexible pipe for reducing bending stress (certain flexible pipe has to be developed)

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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, 2.
9. Satoshi Akagawa, Scott L. Huang, Syunji Kanie, and Masami Fukuda, 2012. Movement due to heave and thaw settlement of a full-scale test chilled gas pipeline constructed in Fairbanks Alaska, 2nd ATC, CD distribution, Paper Number; 23733, Houston Texas.
10. Syunji Kanie, Satoshi Akagawa, Koui Kim and Takashi Mikami, 2006. Estimation method of frost heaving for chilled gas pipeline buried in frost susceptible soil, 2006. ASCE Cold Regions Conference, CD distribution, Bangor, Maine.