Numerical Simulation of Soil Frost Heave around the Buried Oil Pipeline in Permafrost Talik Regions

Zaiguo Fu[1, 2,*], Yu Zhao[1], Bo Yu[1], Yasuo Kawaguchi[2]

1: National Engineering Laboratory for Pipeline Safety, Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Beijing, China
2: Department of Mechanical Engineering, Tokyo University of Science, Chiba, Japan

* Correspondent author: fuzaiguo2009@hotmail.com

Abstract

To analyze the thermal interaction between the buried oil pipeline and the soil around the pipe in permafrost talik regions, a two-dimensional computational model of the soil temperature fields was established based on China-Russia Crude Oil Pipeline (CRCOP) engineering and the heat transfer process with phase change. We solved this model using numerical methods and obtained the freezing characteristics of the soil around the operating pipeline with various influential factors. The developments of the soil frost heave amounts in 4 typical permafrost talik sections within pipeline operation life cycle were predicted and analyzed by combining with Segregated Potential Frost Heave Model. The results indicated that temperatures of the oil transported, insulation layer thicknesses and water contents of soils have significant effects on the freezing characteristics. The largest frost heave amount of the soil under the pipe without thermal insulation layer predicted was 42.3cm in 55% water content talik section after operation for two years.

Keyword: *buried pipeline, permafrost talik regions, phase change, frost heave*

1. Introduction

The buried oil pipeline may face huge challenges for safe operation due to frost heave and thaw settlement deformations which are induced by freezing and thawing process of the soil around the pipe transporting oil with various temperatures. The process is also affected by the change of the atmospheric environment [1, 2]. In permafrost region, the part of perennial non-frozen water due to the outside disturbance or consisting of groundwater passageway is called permafrost talik regions. The soil of talik regions is susceptible to the disturbance imposed by the environment and buried oil pipeline since the start of its operation as the water contained was froze, which may lead to frost heave causing deformation and finally destroying pipeline structure [3].

In order to analyze the soil frost heave and obtain the rules, the complicated heat and mass transfer process including moisture transfer, heat conduction and phase change in the heaving process have been widely studied by the researchers at home and abroad. At present, they usually adopt experiment and numerical simulation to study its characteristics and rule [4]. The experimental studies mostly concentrate on the separate test of temperature, water content, frost heave rate and mechanical characteristics of soils, and a few measures the moisture-heat coupling process [5]. But there are no direct experimental studies on soil freezing characteristics and rules of frost heaving under the thermal effect of the buried oil pipeline. In theoretical and numerical study, the researchers usually attempt to establish and solve the integrated moisture-heat-stress coupling model and obtain the exact soil temperature, moisture and stress parameters [6, 7, 8]. However, the study of three fields coupling was far from sufficient since it is difficult to describe the various thermodynamic parameters and their interaction in theory. Hence, the previous experimental results and theoretical models could not be conveniently used for accurate calculation of soil frost heave in actual buried pipeline engineering.

For the frost heaving problem of the pipeline in talik regions, A.P.S. Selvadurai established and solved the 3D finite element model of interaction between buried pipelines and soil based on simplified moisture thermal coupling effect. The research focused on the induced bending stress on pipe due to frost heave [9]; J.M. Oswell pointed out that the frost heaving deformation of soils under pipeline depends on freezing temperature for unfrozen soil, a source of water to migrate and frost susceptible soil. Several large scale frost heave tests have been conducted and reported by them [10]. In China, the Cold and Arid Regions Environmental and Engineering Research Institute of Chinese Academy of Sciences, the State Key Laboratory of Frozen Soil Engineering, Daqing Oilfields Engineering Design Technology Development Company and other relevant institutions have done certain researches related to soil frost heave around the buried oil pipeline including geological survey, investigation of oil temperature distribution along the CRCOP and properties of soil temperature fields in permafrost regions.

Among them, H.J. Jin et al pointed out that the differentials frost heave of soil may lead to pipe deformation and structure failure, thus it is a main problem in pipe foundation stability study in cold regions [11]. Y.J. Ji et al measured frost-heaving features and ratios of soils from typical geomorphologic units along the pipeline and pointed out the frost-heaving ratio of silty clay with humus sample is the maximum one among the tested samples [12]. G.Y. Li et al analyzed the freezing and thawing processes of the soil around the pipeline by numerical simulation [13]. However, none of them has performed comprehensive analyses of the effects on the freezing rule of the soil with different oil temperatures, different thermal insulation layer thicknesses and different water contents in soils around the pipeline. They could not provide a systematic method to forecast soil frost heave amount along various typical sections of the pipeline.

The main purpose of this study is to simulate the unsteady soil temperature fields in freezing and thawing process by analyzing the thermal effect domain, using the equivalent heat capacity method to cope with latent heat of soils. According to CRCOP design parameters, model of the soil temperature fields around the buried pipeline was established and solved by numerical calculation. The freezing rule and frost heave amount of the soil around the operating pipeline in 4 typical permafrost talik areas with various oil temperatures, thermal insulation thicknesses and water contents were obtained by calculation combining with Segregated Potential Frost Heave Model. This research can ascertain the influencing rules of various factors on soil freezing and supply a systematic method for predicting the soil frost heave amount for the buried pipelines engineering in permafrost talik areas.

2. Modeling

The heat transfer process of the soil around buried oil pipelines in permafrost talik region is usually complicated involving phase change, moisture migration and deformation coupled. To simplify the calculation and achieve a solution satisfying the requirement of engineering application, some assumptions are made in the modelling as follows: (1) the pipe wall, coating and soil replacement in the pipe ditch have no effects on the soil temperature fields with long time scale [14]; (2) the oil temperature on the cross-section of pipe is assumed to be constant, meaning the oil temperature is only a function of time and the axial location; (3) the soil is homogeneous and the heat conduction of soil along the pipe axis direction is ignored and the effects of moisture transfer on long time scaled temperature fields are also ignored [15].

2.1 Geometric model

Some researchers introduced finite thermal-influenced region for buried pipelines in non-permafrost areas and deemed that soil temperature near the oil pipeline is affected much greater than its counterpart far away from the pipe from an engineering perspective [16]. For the pipeline in permafrost talik regions, the similar method was adopted to determine the appropriate size of the heat affected domain. According to the results of geological survey for CRCOP [17], the unilateral horizontal distance is assumed to be 15m for buried oil pipeline of large diameter. In addition, since the temperature gradient is stable all year around at the location of 20m below the ground, hence the vertical depth heat affected is assumed to be 20m.

The thermal properties of the soil at the depth of 20m below the ground surface are of large difference. According to geological survey along the pipeline, the soil around the pipeline can be divided into three layers by the soil types in the domain. The first layer at the depth of 3m below the ground consists of sand loam. The second layer at the depth of 3-10m consists of silty clay soil mainly. The third layer at the depth of 10-20m consists of bedrock mainly. Thus the computational region is divided into three corresponding subfields as shown in Fig. 1. The nominal buried depth and diameter of the pipe were set to be 1.5m and 0.813m respectively. And parts of the pipeline sections had thermal insulation layer of 80mm thickness according to the design parameters of CRCOP (the section in China).

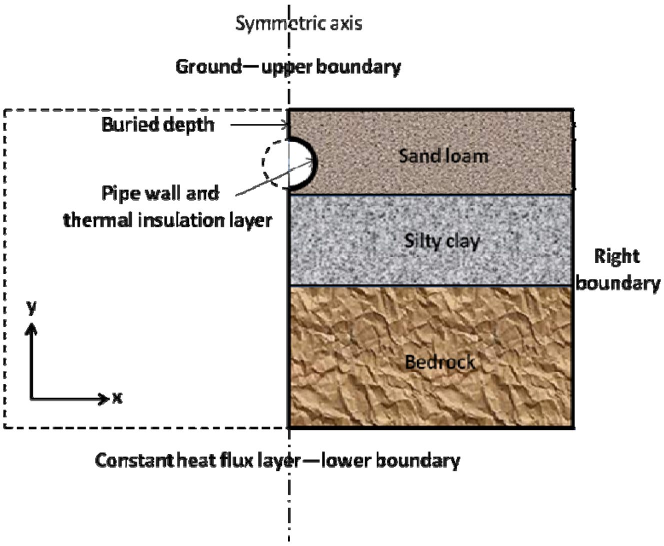


Fig. 1 Sketch Map of Buried Oil Pipe in Permafrost Talik Regions

2.2 Governing equations

The equivalent heat capacity was adopted to replace the latent heat of phase change according to the temperature condition of soil. The governing equation of soil temperature fields is as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) \tag{1}$$

Where c_p denotes the heat capacity of soil and λ is the thermal conductivity according to the temperature condition and corresponding freezing-thawing state. They were expressed as follows when T was between T_1 and T_2.

$$c_p = c_f + \frac{c_u - c_f}{T_2 - T_1}(T - T_1) + \frac{L}{1+W}\frac{\Delta W}{\Delta T} \tag{2}$$

$$\lambda = \lambda_f + \frac{\lambda_u - \lambda_f}{T_2 - T_1}(T - T_1) \tag{3}$$

Where c_f , c_u are heat capacities of frozen soil and unfrozen soil, respectively. λ_f , λ_u are thermal conductivities of frozen soil and unfrozen soil. And L is latent heat in ice-water phase transition. T_1 is the frozen temperature and T_2 is the phase transition temperature. ΔT is a small temperature range. W is total water content and ΔW is the change of frozen water content in a small temperature range.

The heat conduction equation of the thermal insulation layer outside the pipe wall in the polar coordinates can be written as below:

$$\rho^* c_p{}^* \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda^* r \frac{\partial T}{\partial r}) + \frac{1}{r^2}\frac{\partial}{\partial \theta}(\lambda^* \frac{\partial T}{\partial \theta}) \tag{4}$$

The Segregated Potential Frost Heave Model [18] adopted in this research is given as Eq. (5). The frost heave was assumed to be composed of segregation frost induced by water migrating and freezing from outside, and frost in situ causing by pore water freezing. The former frost makes volume increase approximate 1.09 times. Meanwhile, the latter one makes volume increase about 0.09 times.

$$\Delta H = \Delta h_f + 0.09\eta\Delta Z = 1.09 SP_0 gradT(t)\Delta t + 0.09\eta\Delta Z \tag{5}$$

Where ΔH is the value of frost heave. Δh_f is segregation frost and SP_0 is segregated potential which can be calculated by $SP_0 = a\exp(-bP_e)$. a and b are the parameters related to the soil type. P_e is external physical loads. $gradT(t)$ is temperature gradient at the given time. Δt is time for freezing. η is porosity of soil. ΔZ is displacement of the freezing front in time Δt.

2.3 Boundary conditions

The upper boundary of the soil temperature fields model is assumed to be first boundary condition, which is temperature of the ground surface as a periodic function. Considering the atmospheric temperature has risen by 2.4K in the last 50 years, the function can be written as follows.

$$f(t) = T' + A\sin(\frac{2\pi t}{360} + \frac{\pi}{2}) + \frac{2.4}{50\times 360}t \tag{6}$$

Where T' is the average temperature of the ground surface in a whole year and A is the amplitude of the change.

Two typical functions were obtained by regression analysis using least square method for the talik regions along the pipeline. The average temperature is 274.15K and 275.15K with both amplitudes being 19K, respectively. The corresponding soil was defined as low-temperature (cold) and high-temperature (hot) unfrozen soil.

Considering the symmetry of the whole computational region, half the domain is chosen as the calculation area. So the left boundary not including pipe is symmetrical boundary while the right boundary is not thermally affected by the pipe. They can be formulated as follows.

$$\frac{\partial T}{\partial x} = 0 \tag{7}$$

The pipe is a major boundary in the model which is assumed to be first boundary condition being constant temperature. The temperature is same as the uniform oil temperature in pipe based on the assumption. One function of sinusoidal variation can be obtained by the least square method based on the inlet design oil temperature as follows:

$$T = 272.65 + 5.2\sin(2\pi t/360 + \pi/3) \tag{8}$$

Where $\pi/3$ is the initial phase.

The lower boundary of the soil temperature model presented below is assumed to be second boundary condition being constant heat flux as Eq. (9). The temperature gradient at the location of 20 m below the surface is -0.04 K/m along CRCOP (the section in China) [16].

$$q = -\lambda\frac{\partial T}{\partial y} \tag{9}$$

2.4 Other parameters

The basic thermalphysical parameters of various materials involved in the soil temperature fields model are set as same as Ref. [2]. The thermalphysical parameters and equivalent heat capacities of silty clay soil of various water contents are selected from Ref. [19]. The important equivalent heat capacities of soils with average water content in various layers according to the different temperature ranges are shown in Table 1.

For calculating the segregated potential during the freezing process, the parameters a and b of the sand loam around the pipe are set to be 1.45×10^{-8} $m^2/(s\bullet K)$ and 0.015×10^{-3} Pa^{-1}, respectively. And the porosity of soil is assumed to be 10% generally [20].

Table 1 Equivalent Heat Capacities (J/(kg•K)) of Soil with the Average Water Content [19].

Soils	Temperature（K）								
	263.15~253.15	268.15~263.15	270.15~268.15	271.15~270.15	272.15~271.15	272.65~271.15	272.95~272.65	273.15~272.95	275.15~273.15
sand loam	982	1156	1782	3367	5578	18699	30353	66724	1273
silty clay	1158	1693	2650	6727	6758	12142	37137	68372	1466
bedrock	982	1476	2364	3658	6160	16081	39563	1267	1272

3. Numerical Method

3.1 Grids

A Delaunay triangulation method is used to generate grids for the soil domain automatically and structured quadrilateral grids in the polar coordinate system are generated for the thermal insulation layer domain as shown in Fig. 2. Since the temperature gradient is greater in the region near the pipe, denser grids are generated in the region close to the pipeline without overlapping each other.

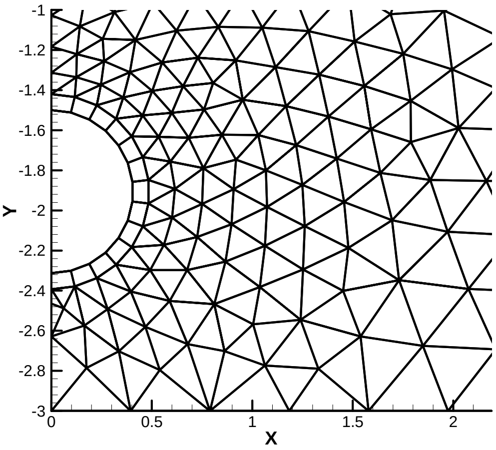


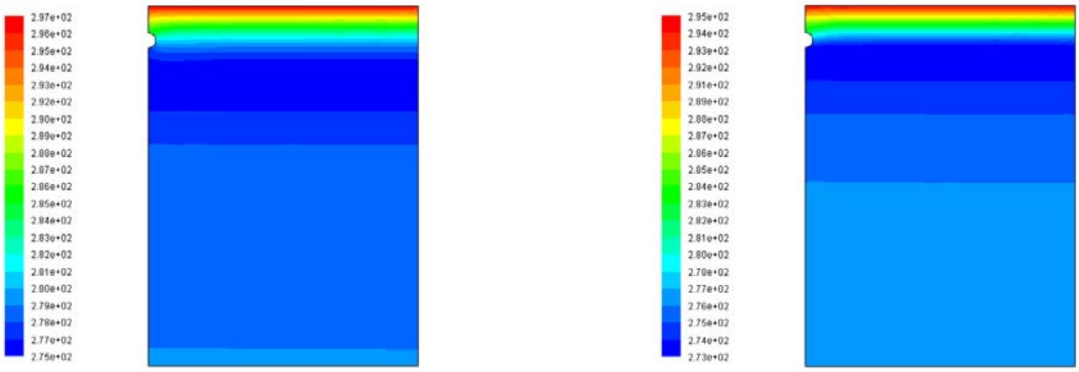
Fig. 2 Grids of Calculation Domain around the Pipe

3.2 Establishment of initial fields

It is important to obtain accurate initial soil temperature fields around the pipeline by numerical method for analyzing the soil frost heave process. The initial fields can be used to verify the model and calculate unsteady temperature fields further. The climate warming was ignored in the ground surface temperature function as Eq. (6) and the boundary of pipe was assumed to be adiabatic when we calculated the initial fields.

The widely applied commercial software FLUENT was adopted in this study. User Defined Functions were used to describe different thermalphysical parameters of various sorts of soils and time-dependent boundary conditions of the model in the software. The heat conduction equation was discreted by the second order upwind scheme and the time step was chosen as 86400s. The calculation had proceeded for a period of 50-100 years until the soil temperature reaches constant at the same position in the area of seasonal varying temperature at the same time in continuous years, meanwhile, the temperature fields in other areas in the calculation domain remain stable.

CRCOP (the section in China) was put into operation in autumn, and one week was needed to fill up the pipeline with oil. It is difficult to determine the exact initial time for different typical sections of the pipeline. As long as the initial boundary conditions are guaranteed to correspond with the time, the initial soil temperature fields of any time in one year do not affect the prediction results in operation of long time scales. In this research, July 15th, the day in hottest month is selected as the initial time for the convenience of calculation. The initial soil temperature fields on the commissioning date of pipeline are shown in Fig. 3. Fig. 3(a) corresponds to high-temperature (hot) unfrozen soil of temperature from 275.15K to 280.15K under pipeline and Fig. 3(b) represents low-temperature (cold) unfrozen soil of average temperature being 274.65K. These properties are similar with the features of the permafrost talik regions in the classic literature [20].



(a) (b)

Fig. 3 Initial Soil Temperature Fields of Permafrost Talik Regions as, (a) Hot-temperature and (b) Cold temperature.

3.3 Validation

The temperature distribution of the plumb line with 10 m horizontal distance from the central axis of the pipeline in the calculation domain was chosen to be the evaluation subject. Fig. 4 presents the calculation results of the subject together with the actually measured temperatures in different depths of the same plumb line in some talik regions near Jia station along the pipeline in July of summer. It can be found the calculation results of the soil natural temperature distribution are in good agreement with the measured values with the maximum deviation being not more than 1.5K, validating the accuracy and reliability of the models and numerical calculations.

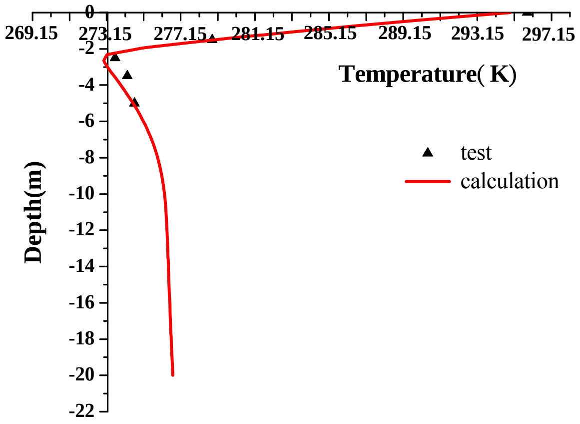


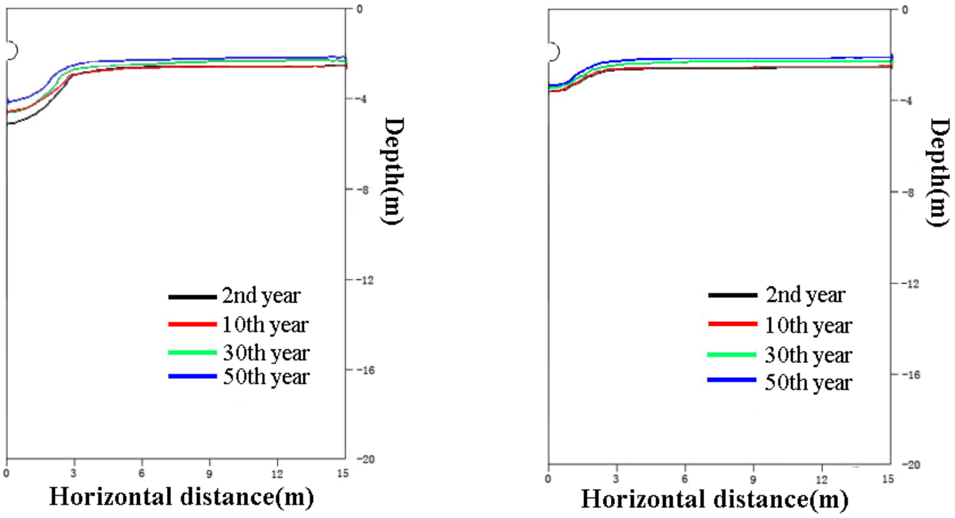
Fig. 4 Distribution of Soil Temperature in Different Depths near Jia Station

4. Results and Discussions

According to the water-bearing character of permafrost talik region along the pipeline, the four typical talik sections of 20%, 25%, 35% and 55% water content in soil have been selected as research objects to analyze the freezing characteristics and predict the frost heave amount. The hot and cold temperature fields of unfrozen soil as established in Section 3.3 were adopted for initial temperature fields. The operation oil temperature was considered to be constant (267.15K, 269.15K and 271.15K) and varies in a sinusoidal pattern as expressed in Eq. (8). The thermal insulation layer thicknesses were assumed 0 mm (corresponding to no heat preservation), 10 mm, 80 mm and 120 mm respectively. The developing processes of the maximum freezing circle (273.15K isothermal lines) around the pipeline with these different parameters were simulated and analyzed to determine the change of the maximum frost penetration and frost heave amount under the pipe during the pipeline operation life cycle (50 years).

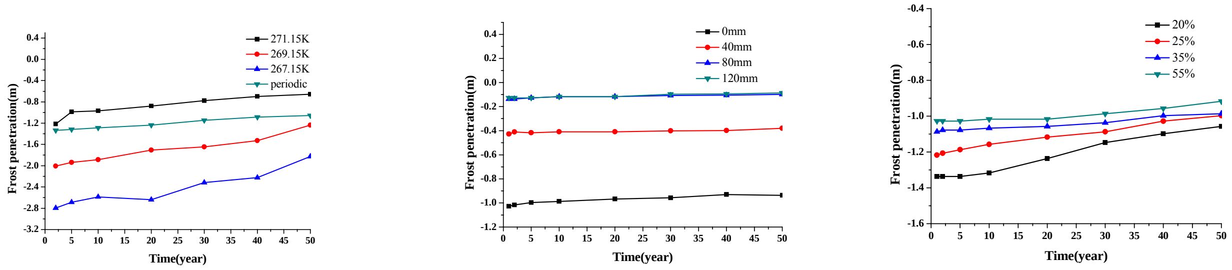
4.1 Influences of different factors

The developments of the maximum freezing circle on March 15th (Change of soil temperature lags 2 months behind the surface temperature) in representative years within pipeline operation life cycle for different factors such as oil temperature were investigated. Fig. 5(a) is the result of oil temperatures of 267.15K for cold unfrozen soil of 20% water content around the pipe without heat preservation. Fig. 5(b) is the result of insulation layer thicknesses of 0 mm for cold unfrozen soil of 20% water content and the periodic oil temperature as Eq. (8). In this study we also performed numerical calculations with other oil temperature as 271.15K, other layer thickness as 80mm and other water content as 55% to compare. Limited to the space, some results of freezing circle are not shown in this paper. Fig. 6 shows variation in maximum frost penetration under pipeline with different parameters (oil temperature, thermal insulation layer thickness and water content) during the operation period.



(a) (b)

Fig. 5 Development of the Maximum Freezing Circle around the Pipeline with Different Oil Temperature as, (a)267.15K and (b) Periodic function.



(a) (b) (c)

Fig. 6 Variation in Maximum Frost Penetration under Pipeline with Different, (a) Oil Temperature, (b) Insulation Layer Thickness, and (c) Water Content in Soil.

From Fig.5, it can be seen that the maximum freezing circle annual around the pipeline in permafrost talik regions decrease with time elapses when the pipeline is operated with negative and periodic oil temperature based on results not shown. Furthermore, the variation trend of the freezing cylinder is smooth during the operation. We also obtain that the maximum freezing circle with 271.15K oil temperature is smaller than that with 267.15K oil temperature in the other same situations. The lower the oil temperature is, the bigger size of the maximum freezing circle can be obtained. And with the other same parameters, the maximum freezing circle annual of the soil around the pipe with 80mm thermal insulation thickness is much smaller than the case without heat preservation. The heat absorption of the soil from the pipe can be decreased by the thermal insulation layer obviously. The thicker the layer is, the harder the unfrozen soil around the pipe turn to be freezing due to the oil of negative temperature. And the maximum freezing circle annual of the soil of 20% water content is slightly bigger than the case of 35% water content with the other same parameters.

From Fig.6, we can see that the maximum frost penetration annual under the pipe decreased with the increasing water content. For the cold unfrozen soil of 20% water content, the maximum frost penetration appears in the second year after operation as 2.8m with the 267.15K oil temperature. On the contrary, the 271.15K oil temperature has less effect on the soil freezing. With the periodic oil temperature as Eq. (8), the soil freezing and thawing may develop alternately because of the positive and negative effect of the oil. So the maximum frost penetration in the second year under this condition as 1.34m is between the case of 271.15K and 269.15K. For the cold unfrozen soil of 55% water content, the maximum frost penetration as 1.03m also appears in the second year after operation with the periodic oil temperature which is 0.3m smaller than the case of 20% water content. In addition, the maximum frost penetration at the position far away from the pipe decreases annually due to the rise of the atmospheric temperature. At project site, close attention should be paid to the probable large increase of the frost penetration in talik region when the atmosphere becomes cold-weather extremes. The frost penetration under the pipe may increase accordingly.

4.2 Frost heave in typical sections

In this part, oil temperature in pipe is set to vary in a sinusoidal pattern as Eq. (8) according to the design condition of CRCOP (the section in China). Considering the monthly frost penetration and the temperature gradient of the freezing front from freezing month in the second year after operation, the maximum frost heave amount under pipeline in 3 typical sections(20%, 25% and 35% water content) during operation life cycle were calculated for two initial temperature conditions of high-temperature and low-temperature firstly by using Eq. (5) . Especially for the talik section of 55% water content, the design thermal insulation layer was neglected to calculate the maximum heave frost amount of the cold unfrozen soil for considering the

Table 2 Monthly Frost Penetration (m) and Average Temperature Gradient (K/m) of the Freezing Front in Typical Talik in the Second Year.

Temperature condition	Time (month)	Types of talik			
		20%	25%	35%	55%
hot	Nov.	0.030/8.51	0.038/8.37	0.054/9.28	-
	Dec.	0.31/4.57	0.031/5.04	0.42/4.54	
	Jan.	0.62/0.79	0.63/2.95	0.75/2.00	
	Feb.	0.91/0.72	0.89/0.80	0.99/0.23	
	Mar.	1.07/0.00	1.03/0.00	1.08/0. 00	
cold	Nov.	0.05/9.86	0.053/6.39	0.053/9.26	0.058/13.08
	Dec.	0.40/5.07	0.40/4.86	0.31/5.54	0.32/7.16
	Jan.	0.73/2.17	0.74/1.96	0.62/2.94	0.65/1.25
	Feb.	1.06/0.21	1.02/0.05	0.91/0.86	0.91/0. 00
	Mar.	1.34/0.00	1.21/0.00	1.03/0.00	1.03/0. 00

*The left side value is frost penetration (m).

Table 3 Monthly Accumulated Frost Heave (cm) under Pipeline in Typical Talik in the Second Year.

Temperature condition	Time (month)	Types of talik			
		20%	25%	35%	55%
hot	Nov.	09.90	10.00	12.20	-
	Dec.	20.00	21.70	23.70	
	Jan.	21.80	28.20	28.60	
	Feb.	23.40	30.10	29.30	
	Mar.	23.60	30.20	29.40	
cold	Nov.	11.40	7.70	12.20	18.60
	Dec.	22.40	18.80	26.30	38.40
	Jan.	26.90	23.10	33.50	42.00
	Feb.	27.60	23.50	35.70	42.20
	Mar.	27.80	23.60	35.80	42.30

worst factors.

Table 2 shows the monthly frost penetration and monthly average temperature gradient of the freezing front in the second year for the 4 sections around the pipeline after the operation. Table 3 gives the monthly frost heave amount accumulated under the pipeline in the second year also for the 4 sections.

According to the calculation results in Table 2, the frost penetrations under the pipeline increase from last November to March in the second year for all the cases. For the sections of 20% and 25% water content, the value of frost penetrations with cold initial temperature condition is bigger than that with the hot condition. The frost penetration decreases with the increasing of water content under low-temperature condition. By contrast, the values of frost penetration for the other two sections with high and low temperature conditions have no obvious difference. For the sections of cold soil of 35% and 55% water content, the values of frost penetration are quite close. The largest frost penetrations are slightly less than the values of the sections with 20% and 25% water content. In addition, since the hot talik soil of 35% water condition have greater diffusing coefficient than that of cold soil, the maximum frost penetration is also slightly larger than that under low-temperature condition.

From Table 2 we can also see that the temperature gradients of the freezing front for the 4 sections decrease month by month. It can be attributed to the decreasing temperature difference between the adjacent soils in the heat transfer process.

It can be seen from Table 3 that the frost heave amounts under the pipeline increase monthly in the second year for all the cases. The frost heaves develop quickly in the first 3 months from freezing moment but smoothly in the later 2 months till March. The maximum frost heave amount of the cold talik section with 20% water content is 0.278m under the effects of periodic oil temperature and atmospheric environment. The maximum frost heave amount of the hot talik section with 25% water content is 0.302m under the same parameters which are bigger than those of the cold soil condition due to the large temperature gradient at the freezing front in such conditions. As the water content increase, the maximum frost heave amount of the cold talik sections with 35% and 55% water content can change from 0.358m to 0.423m.

Thus, the relationship between the maximum frost heave amount and water content in soil during the pipeline operation lacks in regularity owing to the combined effect of temperature gradient at the freezing front and diffusing coefficient of the soil. The segregation frost part is dominated in the total frost heave under the periodic oil temperature. It is mainly determined by soil loads and temperature gradients. In design condition of CRCOP (the section in China), the pipe should be wrapped by thermal insulation layer to protect the structure if the water content in soil in the talik section of pipe crossing overpasses 55%. However, the layer may become invalid after broken and it will seriously impact on the soil around the pipe to cause freezing. Then a certain heave deformation may appear under the pipeline.

5. Conclusions

The model of the soil temperature fields with phase change around the buried pipeline was established and frost heaving characteristics were determined based on CRCOP engineering in this study. The freezing circle and the maximum frost heaves of four typical sections with two initial temperature conditions under different factors were obtained by numerical simulation combining with Segregated Potential Frost Heave Model. The results indicated that this numerical method could simulate the unsteady soil temperature fields around the buried pipeline in permafrost talik region effectively and thus provide guidance for safe operation. The conclusions are as follows:

(1) The maximum freezing sizes around the oil pipeline decrease with time elapses under different conditions. With the decrease of oil temperature in operation and water content in soil, the maximum freezing circle and frost penetration may increase under the same operation conditions.

(2) Thermal insulation layer can effectively restrain the freezing of unfrozen soil around the pipe in talik region. The thicker the insulation layer is, the smaller freezing circle and frost penetration will be. Close attention should be paid to the broken and invalid of the insulation layer.

(3) The maximum frost heave amounts of the sections with 35% and 55% water content are larger than the cases of 20% and 25% water content. For the cold talik section of 55% water content, the maximum value is 0.423m under the pipeline without heat preservation.

Acknowledgements

The supports by the National Science Foundation of China (No.51176204; No.51134006) and Japanese MEXT scholarship to this study are acknowledged and highly appreciated.

References

[1] H.J. Jin, W.B. Yu and Y.C. Cheng, "(Differential) Frost Heave and Thaw Settlement in the Engineering Design and Construction of Oil Pipelines in Permafrost Regions: A Review", *Journal of Glaciology and Geocryology,* Vol. 27, No. 3, (2005), pp 454-464.(in Chinese)

[2] Zaiguo FU, Bo YU, Jie ZHU and Wang LI, "Thaw characteristics of soil around buried pipeline in permafrost regions based on numerical simulation of temperature fields", *Journal of thermal science and Technology*, Vol. 7, No. 1, (2012), pp 322-333.

[3] Jin Huijun, Brewer M C. "Experiences and lessons learned in the engineering design and construction in the Alaska Arctic", *Journal of Glaciology and Geocryology*, Vol. 27, No. 1, (2005), pp 140-145. (in Chinese)

[4] Z.G. Fu, B. Yu, "Research on Moisture -Heat-Stress Fields of the Soil around Oil Pipeline in Permafrost Region", *Oil & Gas Storage and Transportation*, Vol. 29, No. 8, (2010), pp 565-570. (in Chinese)

[5] W. Kunio, W. Tomomi, "Measurement of unfrozen water content and relative permittivity of frozen unsaturated soil using NMR and TDR", *Cold Regions Science and Technology*, Vol. 59, No. 1, (2009), pp 34-41.

[6] Harlan R L, "Analysis of coupled heat-fluid transport in partially frozen soil", *Journal of water Resources Research*, Vol. 19, No. 5, (1973), pp 1314-1323.

[7] Shen Mu, Branko ladanyi, "Modeling of coupled heat, moisture and stress field freezing soil", *Cold Regions Science and Technology*, Vol. 14, No. 3, (1987), pp 237-246.

[8] A.P.S. Selvadurai, J. Hu,I. Konuk, "Computational modelling of frost heave induced soil–pipeline interaction I. Modelling of frost heave", *Cold Regions Science and Technology*, Vol. 29, No. 3, (1999), pp 215-228.

[9] A.P.S. Selvadurai, "Computational modelling of frost heave induced soil–pipeline interaction II. Modelling of experiments at the Caen test facility", *Cold Regions Science and Technology*, Vol. 29, No. 3, (1999), pp 229-257.

[10] J. M. Oswell, "Pipelines in permafrost: geotechnical issues and lessons", *Canadian Geotechnical Journal*, Vol. 48, No. 9, (2011), pp 1412-1431.

[11] H.J. Jin, "Design and construction of a large-diameter crude oil pipeline in Northeastern China: A special issue on permafrost pipeline", *Cold Regions Science and Technology*, 64: 209-212, 2010. Vol. 64, No. 3, (2010), pp 209-212.

[12] Y.j Ji, H.J. Jin, J.m. Zhang and N.w. He, "Experimental Study of the frost-heaving ratio of the typical soil samples along the China-Russia crude oil pipeline", *Journal of Glaciology and Geocryology*, Vol. 30, No. 2, (2008), pp 296-300. (in Chinese)

[13] G.Y. Li, Y. Sheng and H.J. Jin, "Forecasting the oil temperatures along the proposed China–Russia Crude oil pipeline using quasi 3-D transient heat conduction model", *Cold Regions Science and Technology*, Vol. 64, No. 3, (2010), pp 235-242.

[14] X.G. Cui, J.J. Zhang, "Determination of the thermal influence zone of buried hot oil pipeline on steady operation", *Journal of University of Petroleum, China (Edition of Natural Science)*, Vol. 28, No. 2, (2004), pp 75-78. (in Chinese)

[15] LI Shuxun, WU Tonghua. "Permafrost temperature regime: study method and applied analysis", *Journal of Glaciology and Geocryology*, Vol. 26, No. 4, (2004), pp 377-383. (in Chinese)

[16] H.J. Jin, J.Q. Hao and X.L. Chang, "Zonation and assessment of frozen-ground conditions for engineering geology along the China–Russia crude oil pipeline route from Mo'he to Daqing, Northeastern China", *Cold Regions Science and Technology*, Vol. 64, No. 3, (2010), pp 213-225.

[17] LI Guoyu, JIN Huijun and SHENG Yu, "Recent advances in frozen ground engineering geology survey along the China-Russia Crude Oil Pipeline route(Mo'he-Daqing section)", *Journal of Glaciology and Geocryology*, Vol. 30, No. 1, (2008), pp 170-175 (in Chinese)

[18] Konrad J.M., SHEN M, "2-D frost action modeling using the segregation potential of soils". *Cold Regions Science and Technology*, Vol. 24, No. 3, (1996), pp 263-278.

[19] Y.j Ji, H.J. Jin and G.S Wang, "Thaw-stability assessment of the permafrost foundation soil along the proposed China-Russia crude oil pipeline from Mo'he to Daqing", *Journal of Engineering Geology*. Vol. 18, No. 2, (2010), pp 241-251.(in Chinese)

[20] XU xiaozu, Wang jiacheng and Zhang lixin, "*Physics of frozen soil*", 2nd edition, China: Science press, (2010). (in Chinese)