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Research Article

A Multisource Monitoring Data Coupling Analysis Method for Stress States of Oil Pipelines under Permafrost Thawing Settlement Load

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Thaw settlement is one of the common geohazard threats for safe operation of buried pipelines crossing permafrost regions, as pipes need to bear additional bending stress induced by settlement load. In the presented study, a novel coupled data analysis method was proposed for stress state estimation of buried steel pipeline under thawing settlement load. Multisource data including pipe bending strain derived by inertial measurement unit, pipe longitudinal strain derived by strain gauges, and thawing displacement loads derived by soil temperature monitoring were used to estimate the pipe's mechanical states. Based on the derived data, finite element method-based pipe soil interaction model was established to predict pipe's actual stress distribution. A monitored pipe segment of one crude oil pipeline in northeast China operated since 2010 was adopted as a prototype for the investigation, monitoring data derived in the last ten years was employed to predict the settlement loading, and relative accurate stress results was obtained via the established pipe soil interaction model. The mean absolute error (MAE) of the predicted pipe stresses compared with the monitoring results in 2014, 2017, and 2018 are 5.77%, 12.13%, and 13.55%, respectively. Based on the analyzed stress results, it can be found that the investigated pipe was subjected to an increasing settlement load from 2010–2016, made the bending stress increased up to 149.5 MPa. While after 2016, due to the depth of frost soil in this area is no more than 3.5 m, the thawing settlement load almost remained constant after 2016. As the investigated pipe is made by X65 line pipe steel, the von-Mises stress in pipe is much smaller than the allowable one indicating pipe's structural safety status so far. The proposed method can also be referenced in the status monitoring of buried pipeline crossing other geological hazard regions.

1. Introduction

Crude oil is commonly transported by pipelines in the arctic region. With the rising of crude oil temperature in the pipeline, buried heated oil pipeline with insufficient insulation is always affected by permafrost thawing. Subjected to the thaw settlement load, bending strain can be accumulated in the pipe. The buckling or rupture failures of pipe may happen if bending strain becomes larger than the ultimate strain of pipe [1]. In order to ensure the safe and efficient operation of pipelines in frozen soil areas, lots of researchers and pipeline operators have conducted relative research studies.

Since field monitoring data are the fundamental information reflecting pipe's mechanical states, various monitoring methods have been investigated and developed for pipeline status monitoring. Generally, the permafrost temperature field can be monitored by distributed temperature sensors. The thawing depth around the pipe can be analyzed based on the temperature field results or measured directly. For pipeline itself, commonly pipe strain was monitored to calculate pipe's stress component. While no techniques are able to sensor the absolute strain values in pipe so far, pipe strain components such as the bending strain component or the longitudinal strain increment component are commonly monitored. Pipe bending strains and longitudinal strains can be obtained based on the inertial measurement unit (IMU) and strain gauge monitoring system, respectively. Specifically, Wang et al. [2, 3] presented the layout of one special soil temperature monitoring system at four monitoring sites of an inservice oil pipeline crossing different geohazard areas. Based on the new developed system, variations of the thawing depth around pipe in recent years were obtained. Tan et al. [4] proposed a pipeline displacement monitoring technology based on total station surveying technique, which has been successfully applied in the displacement monitoring in permafrost regions. Li et al. [5–7] performed a series of research studies focusing on bending strain detection via IMU assembled in pipeline inline inspection tool, and this technology was employed by the Petrochina Pipeline Company to identify high thawing settlement risk areas. Similarly, Cho et al. [8] developed a bending strain calculation method of pipe bending strain based on the pipeline coordinates derived by IMU. Inaudi [9] conducted some engineering cases application analysis of this kind of strain monitoring systems. Glisic [10] conducted comparison analysis of strain monitoring results via different fiber optic strain sensors. Lei et al. [11, 12] summarized the dent strain detection methods based on the inline inspection data. Rajeev et al. [13] gave a brief overview of optical fiber technologies and outlined potential applications of these technologies for geotechnical engineering applications. It can be found that although ground temperature, soil displacements, and pipe strain can be derived more or less, the actual stress states of pipe can still not be sensed comprehensively. Witek et al. [14, 15] provided the method for gas leakage rate estimation method based on defect population. Life cycle estimation of high pressure pipeline was conducted based on inline inspection data. The existing monitoring data can only be adopted to estimate current safety status of pipeline approximately. The high-risk locations of pipeline failure may not be accurately identified, and the variation trend of pipeline's stress response cannot be predicted, which will affect the effectiveness of the pipeline safety assessment.

As for the mechanical analysis of buried pipeline subjected to thawing settlement, several related research studies have also been carried out. For instance, Xu et al. [16] investigated the stresses and strains of pipelines by infield experimental tests, which found that peak stress appears near the boundary of the settlement zone. Liu et al. [17] investigated the effects of soil frost heaving displacement and pipe diameter on the critical buckling axial load of buried heated pipeline based on experimental and numerical analysis. Wen et al. [18, 19] deduced an analytical model considering the strain hardening behaviour of pipe steel and analyzed the stress and deformation responses of pipes under various thawing settlement loads. Xia et al. [20, 21] conducted similar parametric analysis investigations focusing on pipe's deflections. Other researchers employed the numerical analysis models based on finite element method to investigate pipe's stress and strain responses under various kinds of thawing settlement loads [22, 23]. As mentioned above, small-scale tests and numerical simulation investigations can be referred in stress and strain analysis of pipeline in permafrost zones. However, it can be found that pipe's loading conditions used in these documented research studies are mainly simplified to some types of assumed soil displacement loads which cannot reflect pipe's actual loading conditions monitored from actual engineering cases. Therefore, it is necessary to combine the multisource monitoring data and numerical simulation technology to improve the accuracy of monitoring results for pipe's actual mechanical states.

In this study, multisource monitoring data were employed. A coupling stress evaluation method of pipeline subjected to thawing settlement based on monitoring results and the numerical model was proposed. In the proposed method, thawing settlement was estimated via the soil temperature results, and a pipe soil interaction model based on finite element method was employed to reveal the actual stress states in pipe. A case study shows that the proposed method can accurately predict pipe's stress distributions in the thawing settlement zone, which successfully fills the gap that some most dangerous sections may not be monitored by distributed sensors. This method is also referable for pipelines located in other geohazard regions.

2. Monitoring System for Pipes in Permafrost Regions

As mentioned above, multisource monitoring data of pipelines can be obtained by different monitoring techniques. For pipeline crossing thaw settlement regions, two kinds of data are commonly needed, i.e., the environmental data and the pipeline strain data. Generally, as shown in Figure 1, the environmental data include the soil temperatures and the ground settlement displacement, and the pipeline strain data include different strain components, i.e., bending strains and longitudinal strains derived by IMU and strain gauges.

Temperature monitoring results can be used to acquire the variation of temperature field, and the characteristic parameters of permafrost regions, such as maximum depth of frozen soil, annual average surface ground temperature. The displacement monitoring results can be used to obtain the frost heave or thawing settlement displacement of some concerned points. Strain monitoring results can be adopted to determine whether the strain value exceeds the pipeline strain capacity. In the following sections, monitoring technologies which have been applied in the Petrochina Company will be introduced briefly.

2.1. Temperature Monitoring System for Frozen Soil. Temperature field monitoring results of permafrost zones can reveal the variations of soil temperature with the seasonal oil temperatures and climatic changing conditions, which can provide an important reference for determining whether the buried pipeline has frost heave or thaw

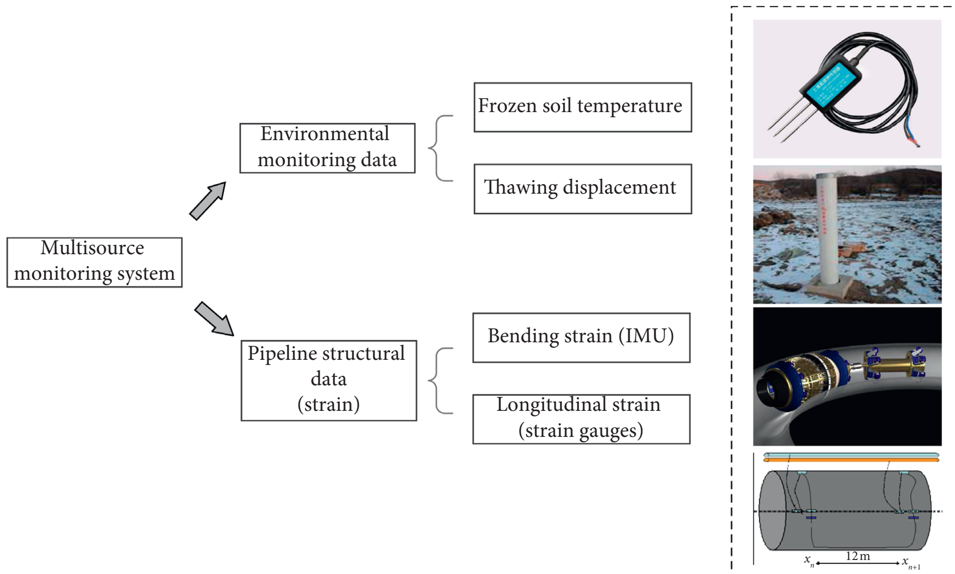


Figure 1: Established monitoring system for pipes in permafrost regions.

settlement hazards. Meanwhile, with detected frozen soil characteristic parameters, the maximum thaw settlement of frozen soil can be predicted by analyzing temperature monitoring data. Figure 2 illustrates the infield temperature system used in Petrochina Company. Commonly temperature sensors are distributed 20 meters away from the pipe axis in the horizontal direction and 15 meters beneath the ground surface in the vertical direction in order to get the whole temperature distribution around pipe.

2.2. Pipeline Strain Detection Based on IMU and Fiber Bragg Grating (FBG) Strain Monitoring. IMU inline inspection tool is one common technique to acquire the position and bending strain of pipeline widely employed by pipeline operators recently. Petrochina Pipeline Company also developed a series of inline inspection tools with the inertial measurement unit since 2014 [5], as shown in Figure 3.

The bending strain and bending strain variation characteristics of the entire pipeline can be acquired based on IMU-detected pipeline coordinate data at different time. Figure 4 shows the pipeline coordinate and strain results of one inspected pipeline in Petrochina Pipeline Company. In order to perform the integrity assessment, Petrochina Pipeline Company suggested strain criteria for IMU-detected bending strain, i.e., the absolute strain value and strain variation value should be less than 0.125% and 0.02%, respectively [22]. Based on the strain criteria acquired from Chinese standard GB 32167 Oil and gas pipeline integrity management specification, pipe segments with large bending strains were detected as shown in Figure 4(a). As can be observed from the figure that the longitude of the pipeline varies from 108.8° to 109.4°, the latitude of the pipeline varies from 34.8° to 35.8°, and the variation range of pipeline altitude is 600–1600.

In addition to IMU-based bending strain measurement, fiber Bragg grating (FBG) strain gauges are used to monitor the real-time strain increment of pipes at high-risk thawing settlement zones. This kind of real-time warning can be helpful for pipeline safety. Figure 5 shows the arrangement of FBG strain gauges on pipes. Generally, three strain gauges are needed for one pipe section, and the longitudinal distance between the monitored pipe sections is set to be around 12 meters.

3. Coupling Data Analysis of Multisource Monitoring Data

Based on multisource monitoring data derived by different sensors, a coupling analysis method was proposed in this study. As shown in Figure 6, the analysis process can be divided into the following steps:

(1) In the first step, the collection and analysis of multisource monitoring data was performed to estimate the possible geohazard types faced by the pipe.

(2) In the second step, an assumed initial surface displacement of thaw settlement area was set based on multisource monitoring results.

(3) In the third step, thaw settlement displacement load derived by the second step was applied to the numerical inversion model, and pipe-soil interaction parameters were derived by the filed investigation results.

(4) In the final step, comparative analysis of pipeline strain detection results and numerical simulation results can be adopted to verify the accuracy of the numerical model. The reliability of numerical results can be improved by adjusting variable parameters of the model to make the performance indices less than allowable criteria. The three indices are the coefficient of determination (R^2), mean absolute error (MAE), and root-mean-square-error (RMSE). These indices are commonly used in performance assessment of prediction models. The calculation formulas are listed as follows:

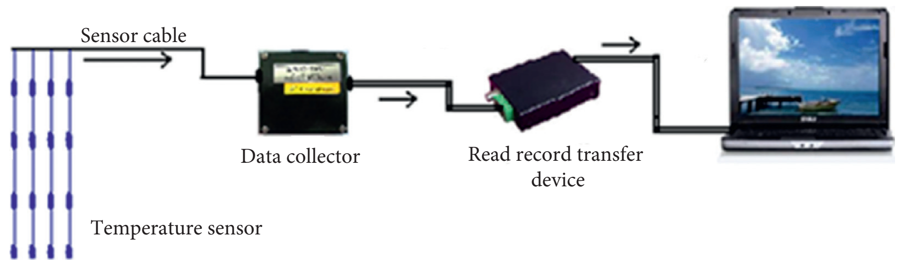


FIGURE 2: Temperature monitoring data acquisition process used in Petrochina Pipeline Company.

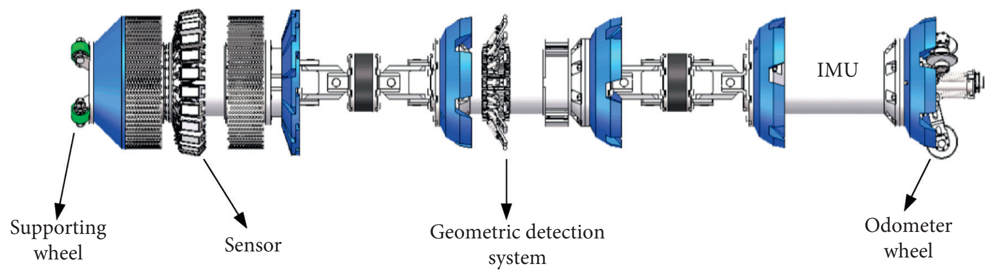


FIGURE 3: Inline inspection tool with IMU developed by Petrochina Pipeline Company.

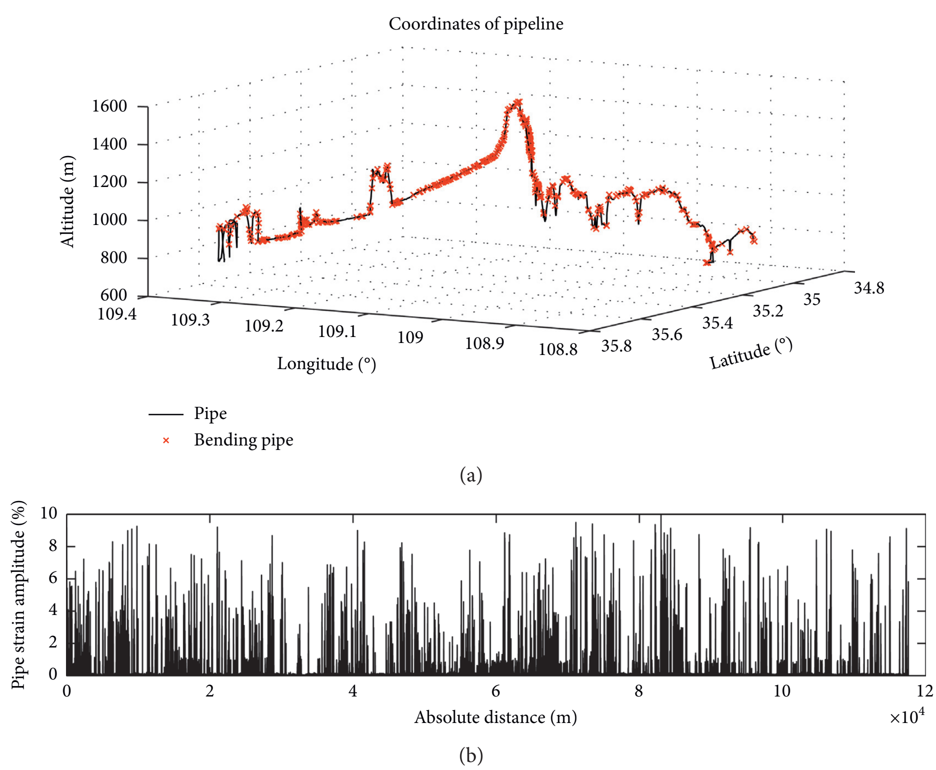


FIGURE 4: Pipe coordinates and pipe strain derived by IMU for one pipeline in China. (a) Pipe coordinates derived by IMU. (b) The primary strain results without treatment derived by IMU.

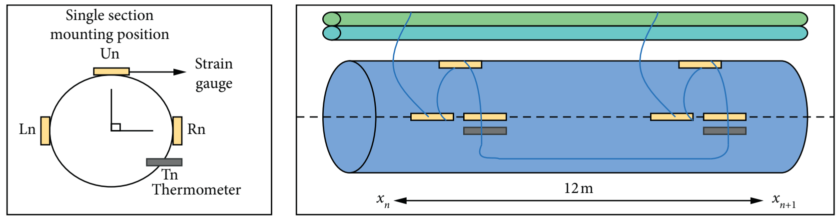


Figure 5: Schematic diagram of FBG monitoring used in Petrochina Pipeline Company.

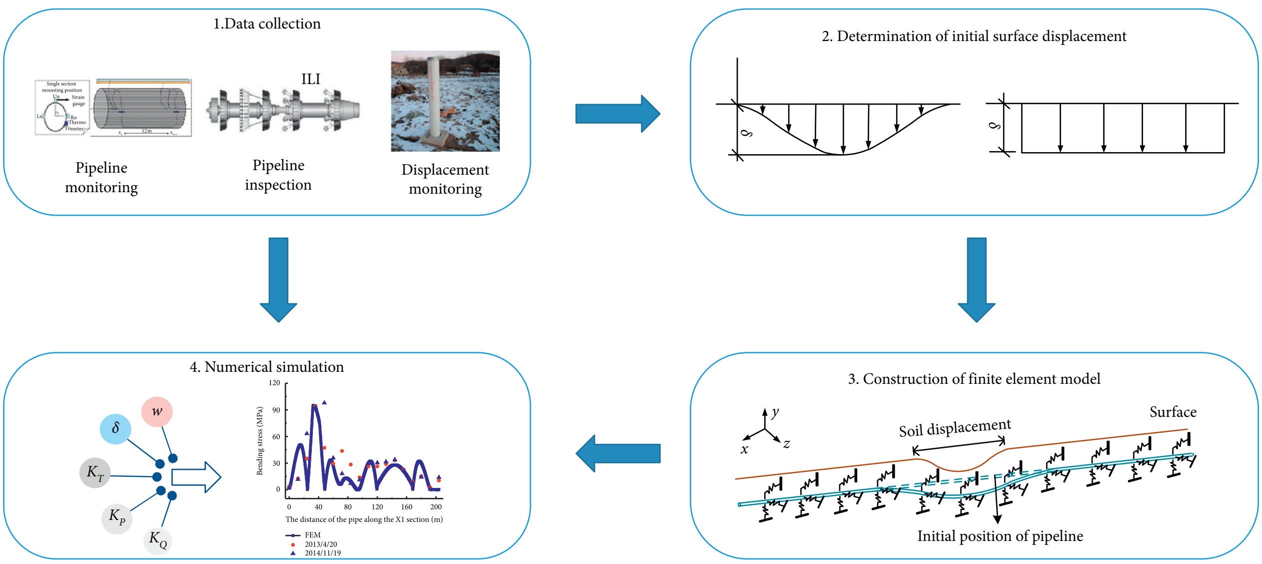


Figure 6: Pipeline coupling data analysis based on data analysis and numerical simulation.

$$\begin{cases} \mathrm{RMSE} = \sqrt{\dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left(\varepsilon_{ei} - \varepsilon_{mi}\right)^2}, \\ R^2 = 1 - \dfrac{\sum_i \left(\varepsilon_{mi} - \varepsilon_{ei}\right)^2}{\sum_i \left(\varepsilon_{mi} - \bar{\varepsilon}_m\right)^2}, \\ \mathrm{MAE} = \dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left|\varepsilon_{ei} - \varepsilon_{mi}\right|. \end{cases} \tag{1}$$

Here, N is the number of strain values, ε_e is the estimated strain value, ε_m is the measured strain value, and $\overline{\varepsilon_m}$ is the average monitored strain values.

The detailed analysis procedure is summarized in Figure 7. The bending strains of the monitored points of pipeline were compared with the measured ones.

4. A Case Study

4.1. Case Description. As shown in Figure 8, the AA007 monitoring pipe segment is located 8.5 km away from the investigated pipeline's initial station. Due to the high moisture of surrounding soil and the rising of crude oil temperature in the pipeline, this area becomes a typical thaw settlement zone. After the operation of the pipe, a comprehensive monitoring system at this location was installed continuously since 2010. As observed in Figure 9, there are 18 monitoring sections set up along the pipeline. The distance between adjacent monitoring sections is about 12 m, i.e., length of a common line pipe segment. Based on filed investigations, the X5-X6 section is located beneath a road, and the pipeline will inevitably be affected by ground surface pressure. Meanwhile, there is a large area of water accumulation at the upstream of X5 section and downstream of X6 section. Due to the existence of thawing area, the thaw settlement risk is significantly increased, which seriously affects the structural safety of the pipe.

4.1.1. Soil Conditions of the Monitored Area. The frozen soil in the monitoring area can be divided into three types depending on the soil's depth beneath the ground surface. As shown in Figure 10, they are sandy loam, silty clay, and weakly weathered base rock, respectively. The buried depth of the pipe was 2.5 m. The pipe diameter and pipe wall thickness are 813 mm and 16 mm, respectively. The soil parameters are listed in Table 1, which were acquired from geological investigation data during the pipe design stage. In the thawing settlement analysis, the ground surface

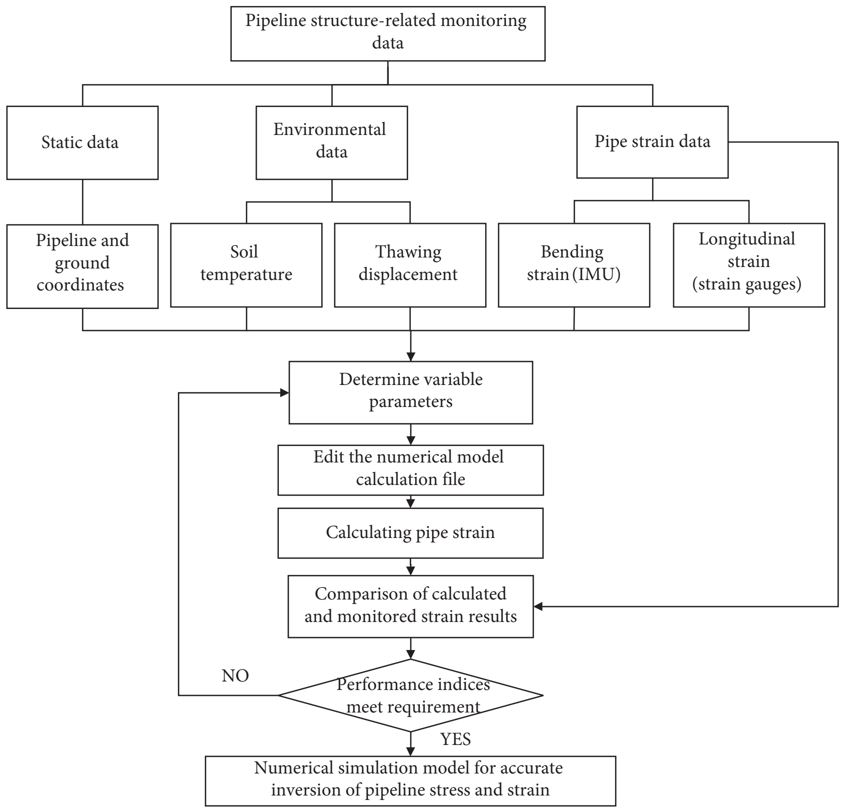


FIGURE 7: Coupling data analysis of pipelines' mechanical state based on multisource sensing data.

(a) (b) (c)

FIGURE 8: Site survey map of AA007.

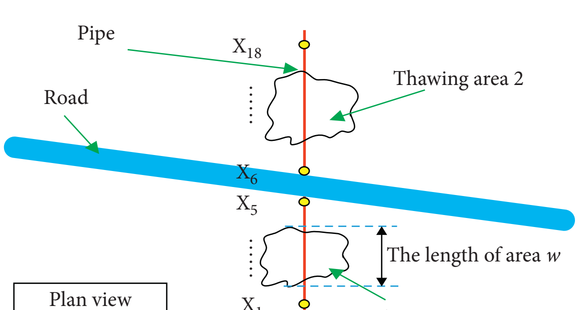


FIGURE 9: Site overview.

displacement can be calculated based on thawing depth of frozen soil and thawing settlement coefficient of the soil.

4.1.2. Trends of Oil Temperatures in the Initial Station. The investigated crude oil pipeline was put into operation in 2010. The initial designed oil temperature was considered to be −6.41°C in winter and 3.65°C in summer. While, after the operation, the oil temperature increased continuously. Recently, the maximum oil temperature in summer has increased up to 28.5°C. Trends of the oil temperature of the initial station between 2014 and 2020 is shown in Figure 11. Increased oil temperature increases the risk of thaw

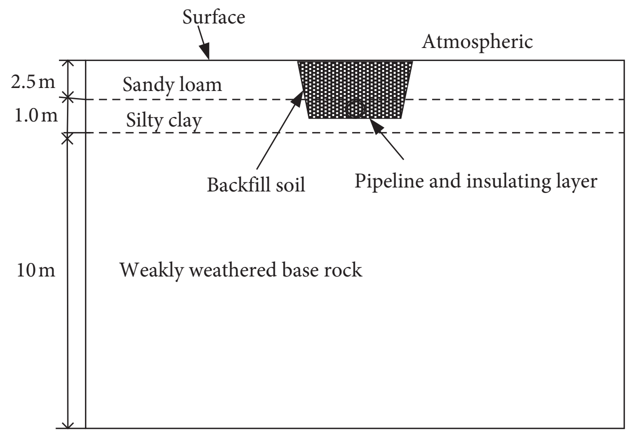


Figure 10: Soil distribution in frozen soil area.

Table 1: Thermal properties of soil layers.

Physical parameters	P	C_f	C_u	λ_f	λ_u
Unit	kg/m^3	10^3 J/(kg·°C)		W/(m·°C)	
Sandy loam	1300	1.49	1.88	1.21	0.84
Silty clay	1600	2.54	3.35	1.04	0.72
Weakly weathered base rock	1600	1.50	1.90	2.12	1.42

ρ: density; C_f: specific heat of frozen soil; C_u: specific heat of unfrozen soil; λ_f: thermal conductivity of frozen soil; λ_u: thermal conductivity of unfrozen soil.

settlement, which makes monitoring of pipe's structural states becomes necessary.

4.2. Multisource Monitoring for the Pipe

4.2.1. Temperature Field Monitoring. The risk of thaw settlement in frozen soil area can be evaluated via detailed analysis of the soil temperature around the pipe. The temperature field monitoring system installed in this area is shown in Figure 12(a). The PT100 temperature sensor was selected to monitor the temperature distribution of frozen soil. There are 6 monitoring lines in every section with 168 temperature sensors installed. The L1 monitoring line is located above the pipeline. The other five monitoring lines are installed away from the pipeline laterally. The L6 monitoring line was set a little further away, which can be adopted to monitor the temperature distribution of the soil surround the pipeline under natural conditions. All the temperature data were collected twice a day and transmitted to the integrity management centre via the devices shown in Figure 12(b).

The soil temperature along L1 monitoring line and L6 monitoring line from August 2016 to June 2018 are plotted in Figure 13. As shown in the figure, soil temperature above the pipe is obviously affected by the seasonal meteorological temperature. As for the L1 monitoring line, the temperature of the soil above the pipe decreases with the increase of depth in summer. However, the temperature is monotonically increasing as the depth increases in winter. As for the L6 monitoring line, the soil temperature basically keeps invariant, when the depth is larger than 6 m. When the buried depth varies from 0 m to 2 m, the temperature of frozen soil rises rapidly, which indicated that the rising of crude oil temperature obviously accelerates the thawing of frozen soil around the pipeline.

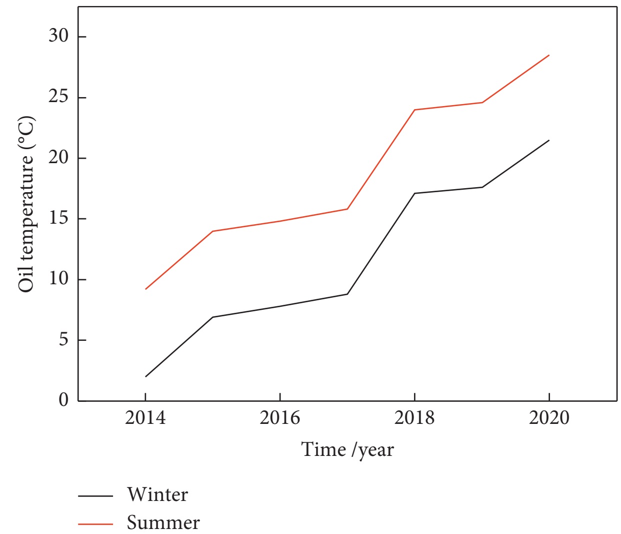
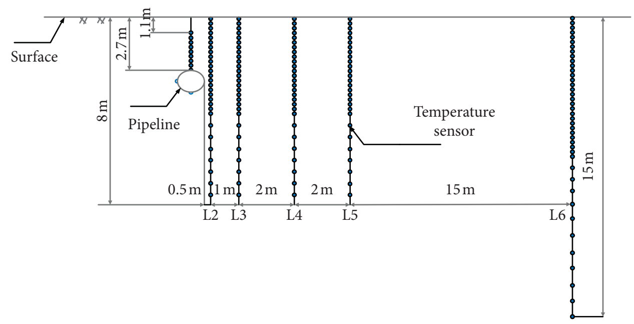


Figure 11: Temperature of oil in initial station of the pipeline.

4.2.2. IMU-Based Bending Strain Detection. IMU monitoring data can be adopted for bending strain analysis of long-distance oil pipeline. Petrochina Pipeline Company has developed several inline inspection tools with IMU modules, which can detect relatively accurate pipe bending strains. Based on the IMU monitoring results, the mechanical state of pipeline can be obtained to a certain extent, which makes quantitative safety assessment of pipelines possible. Figure 14 shows the preparing procedure before the inspection for the considered oil pipeline. Based on the IMU bending strain analysis results, high-risk area with large bending strains can be identified. For this high-risk area, real-time strain monitoring via strain gauges may be considered to ensure pipe's safety.

Figure 15 illustrates the horizontal and vertical bending strain results for the considered pipe segment. Horizontal strain means the bending strain obtained in the horizontal plane, while the vertical strain means the bending strain obtained in the vertical plane. The strain results can be calculated via the coordinates derived by IMU according to reference [22]. The absolute distance of this pipe segment from the initial station varies from 8215 m to 8416 m. It can be readily observed that the variation of horizontal strain is not obvious, which mainly varies from −0.05% to 0.05%. Thus, the bending strain of this pipe segment is mainly caused by vertical settlement. And the vertical strain derived by IMU peaks at 8353 m away from the initial station with the peak value equals 0.71%.

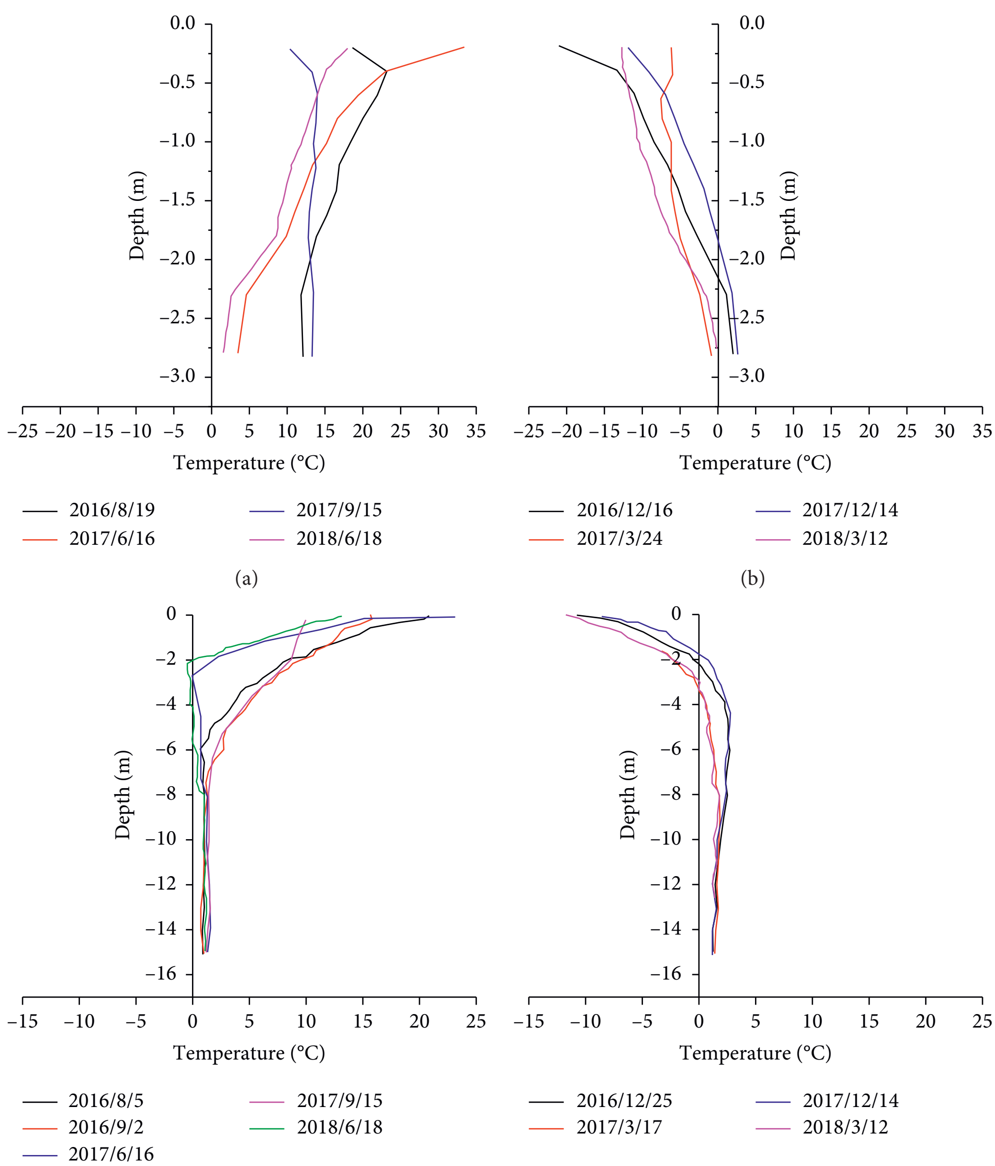
4.2.3. Longitudinal Strain Monitoring. Pipeline's mechanical status also can be monitored via distributed strain gauges.



(a)

(b)

Figure 12: Temperature field monitoring system installed in the field. (a) Arrangement of temperature sensor in one pipe section. (b) Data automatic collection centre with solar power.



(a) (b) (c) (d)

Figure 13: Trends of soil temperature with depth at different positions around the pipe. (a) Summer, L1 monitoring line. (b) Winter, L1 monitoring line. (c) Summer, L6 monitoring line. (d) Winter, L6 monitoring line.

Figure 14: IMU field inspection.

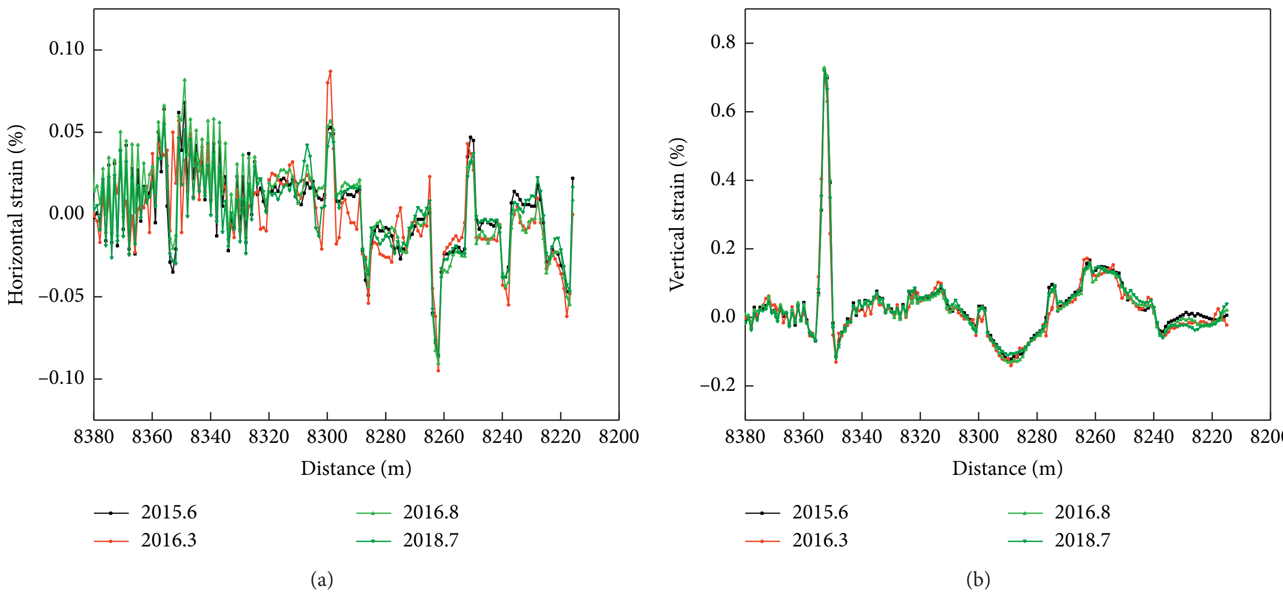


Figure 15: Bending strain derived by IMU. (a) Horizontal strain. (b) Vertical strain.

Due to this is a high thawing risk area, longitudinal strain monitoring of this segment has lasted near 10 years. Some bending stress results calculated by the strain gauges of each monitoring section are illustrated in Figure 16. It can be clearly noticed that, after 2010, bending stress has changed significantly from pipe section X2 to pipe section X6 and from pipe section X10 to pipe section X14. The stress value of X4 section has increased obviously, increasing from 10 MPa in 2010 to 149.5 MPa in 2016. However, the stress of X6 section increased slightly. And after 2016, the bending stress of entire pipeline was basically stable.

The comparative analysis of the IMU bending strain and longitudinal stress monitoring results was conducted. As shown in Figure 17, results derived by different technics show similar peak values and distributions. Especially, the peak stress results obtained by the two detection methods are basically the same.

4.3. Coupling Data Analysis on Pipe's Mechanical States. The key of the proposed coupling data analysis method is the pipe-soil interaction model. Based on the accurate numerical model, multisource monitored data can be taken as input boundary parameter values or output benchmarking targets. By adjusting the numerical model parameters, the true stress and strain distribution in pipe can be obtained, which can be further used in safety assessment.

4.3.1. Numerical Analysis Model. Nonlinear finite element method has been widely applied in the mechanical analysis of pipe structures subjected to geohazard loads. A pipe soil interaction model was established in this paper for the considered X65 steel pipeline. The pipe diameter and pipe wall thickness are 813 mm and 16 mm, respectively. Its operation pressure varies from 4 MPa to 6 MPa. In the numerical model, the pipe was modelled by ELBOW element developed by commercial finite element code package ABAQUS, as this special element can consider pipe's section deformation more accurately comparing with the common pipe elements. In order to eliminate boundary effects, the entire pipe model (Figure 9) was extended to 600 m. As can be observed in Figure 18, a fine mesh with element length of 0.2 m was utilized for the 200 m pipeline in the middle section where settlement zones were located to obtain the accurate mechanical response of pipe subject to thawing

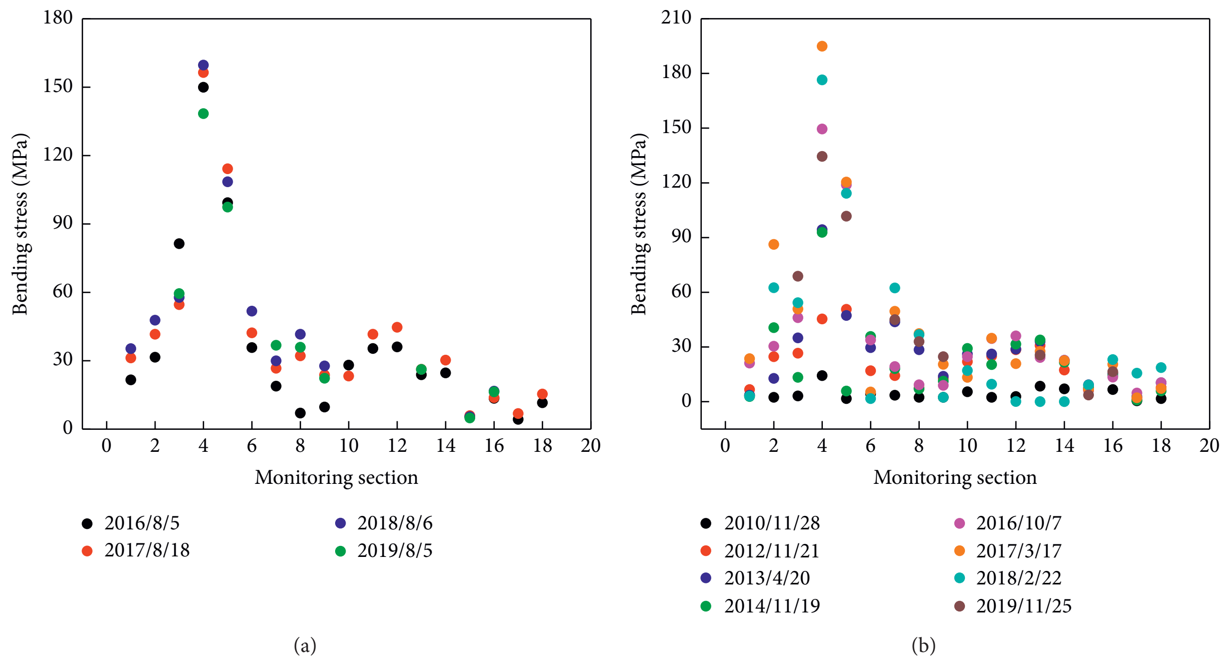


FIGURE 16: Monitor the bending stress distribution. (a) Summer. (b) Winter.

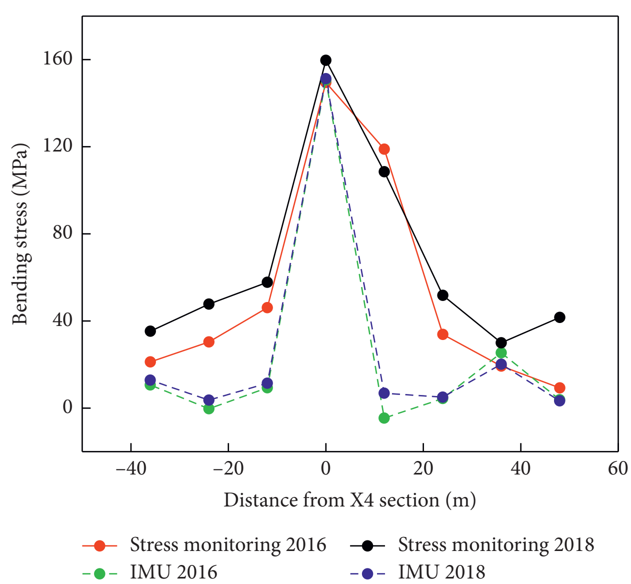


FIGURE 17: Comparison of bending stress and results derived by different methods.

settlement. Meanwhile, a coarse mesh with an element size of 1 m was used for both extended pipes at the two sides.

As shown in Figure 19, the soil resistant force on the pipe can be described by nonlinear springs, which can be realized by the three-dimensional 4-node pipe-soil interaction elements (PSI 34) developed by ABAQUS. The soil spring parameters f_u, p_u, and q_u (q_d) represent the maximum soil resistant forces per unit length of pipes in the axial, lateral, and vertical directions. And x_u, y_u, and z_u (z_d) represent the yield displacements, respectively. The values of these parameters can be calculated by the equations suggested by the ALA-ASCE guideline [24].

In this study, backfill soil in the pipe trench is medium sand with a cohesive stress of 10 kPa, a friction angle of 40°, and an effective unit weight of 20 kN/m^3. However, the site soil is silty clay with a cohesive stress of 10 kPa, a friction angle of 25°, and an effective unit weight of 17.09 kN/m^3. The soil spring models are illustrated in Figure 20. According to ALA-ASCE guideline, axial soil spring parameters were calculated by the backfill soil parameters, while the lateral and vertical soil parameters were calculated by site soil parameters. Thus, the soil spring parameter values can be obtained as listed in Table 2.

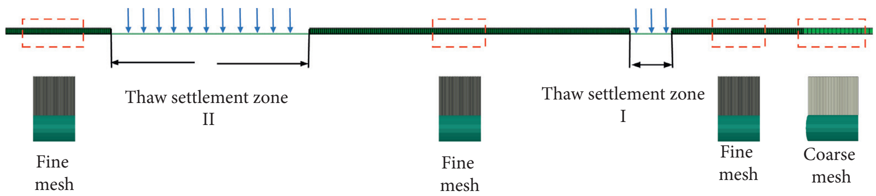


Figure 18: Sketch of the finite element model.

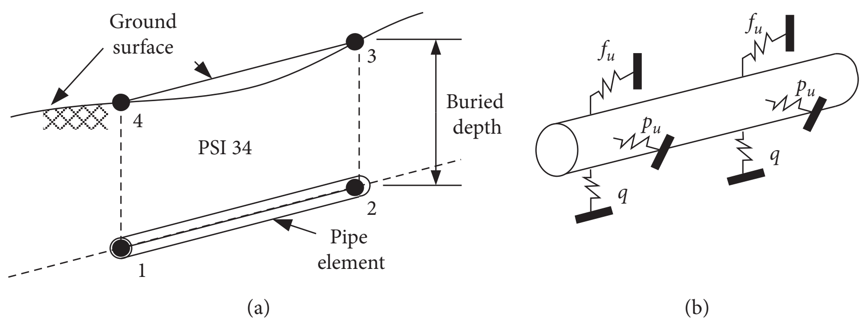


Figure 19: Soil springs simulating soil constraints on pipe. (a) PSI unit in ABAQUS. (b) Spring action mode.

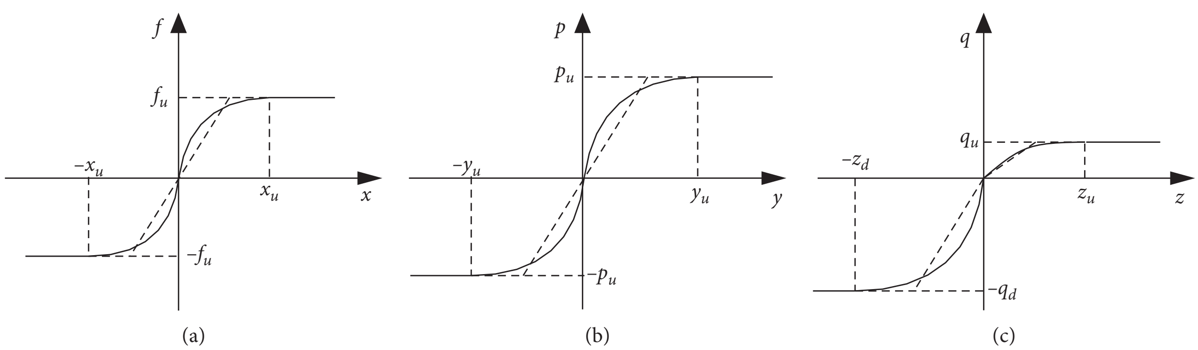


Figure 20: Soil spring model in ASCE guide. (a) Axial. (b) Lateral. (c) Vertical.

Table 2: Nonlinear soil spring parameters.

	Axial soil spring	Lateral soil spring	Vertical bearing soil spring	Vertical uplift soil spring
Peak soil resistant force (kN/m)	42.9	567.9	3486.8	112
Yield displacement (mm)	5	104.3	101.6	30

In the numerical model, two loading steps were needed. In the first operation load step, internal pressure and temperature loading were applied on the entire pipe. In the second settlement load step, the thaw settlement displacement was applied to the pipe segments in the thawing area. From the field investigation, it can be found that thawing depth of the two thawing area locating from pipe section X2 to pipe section X4 and from pipe section X10 to pipe section X14 should be the same, while the surface loading induced by the road increased the settlement of the X2-X4 zone. Approximate settlement displacements for these two areas were set to be 0.35 m and 0.21 m first. The displacement value can be adjusted during the data analysis process. Figure 21 shows the sketch of the established numerical model.

4.3.2. Mechanical Response of Pipeline in the Thawing Settlement Zone via Coupling Data Analysis. Vertical displacement results of the pipe in 2017 based on the established model and assumed parameters are shown in Figure 22. Due to thaw settlement displacement in zone I is larger, the pipe displacement is also larger. The maximum pipe vertical displacement was 0.36 m in 2017. Figure 23 illustrates the contour plots of the finite element model.

Figure 24 illustrates the comparison results of the multidata-based numerical model and the bending stress values monitored by distributed strain gauges. The results in 2014, 2017, and 2018 were shown as prototypes. Based on the numerical model, variations of pipe's bending stress in the high thawing settlement zone were derived, which can fill the

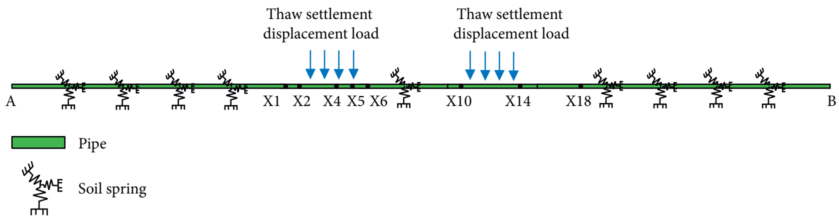


Figure 21: Schematic diagram of model boundary conditions.

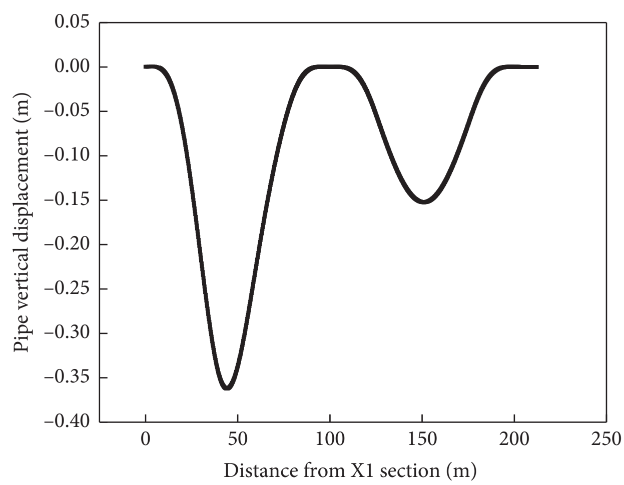


Figure 22: Pipe vertical displacement distribution along the pipe axis (2017/6).

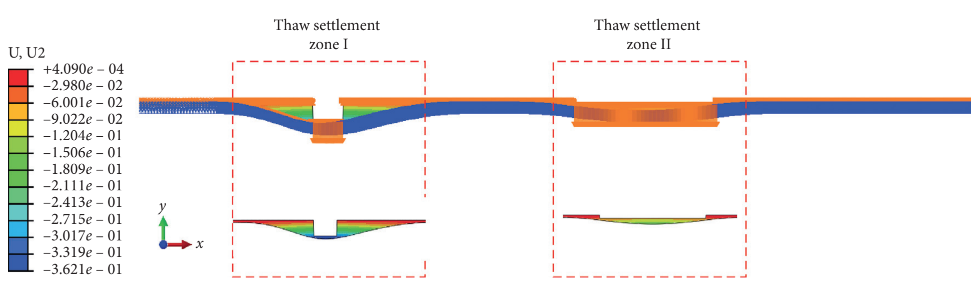


Figure 23: Vertical displacement contour results (2017/6).

gap that the strain gauge monitoring system can only monitor 18 pipe sections.

Performance of the proposed method was further studied using three indices, i.e., the coefficient of determination (R^2), mean absolute error (MAE), and root-mean-square-error (RMSE). As shown in Table 3, relatively good results were obtained for all the three years, which reflects that the proposed numerical model can predict pipe's structural status reasonably.

Based on the validated numerical model, variations of the peak bending stress, i.e., the bending stress of X4 section from 2010 to 2018 are further discussed as shown in Figure 25. It can be found that, the bending stress of pipeline due to thaw settlement of permafrost significantly increased before 2016. However, the value of bending stress changes slightly from 2016 to 2018, which is due to the fact that thaw depth has reached the maximum depth of frozen soil. As soil constraint stiffness may increase a little in winter, the bending stress of pipeline is slightly larger than that in summer. In general, the maximum Mises stress in pipeline is 282 MPa, which is less than the allowable stress, i.e., 0.9 σ_s (SMYS of X65 line pipe steel, 405 MPa). The comparative analysis of numerical simulation results and stress detection results show that the numerical inversion model can accurately reflect pipe's true mechanical status.

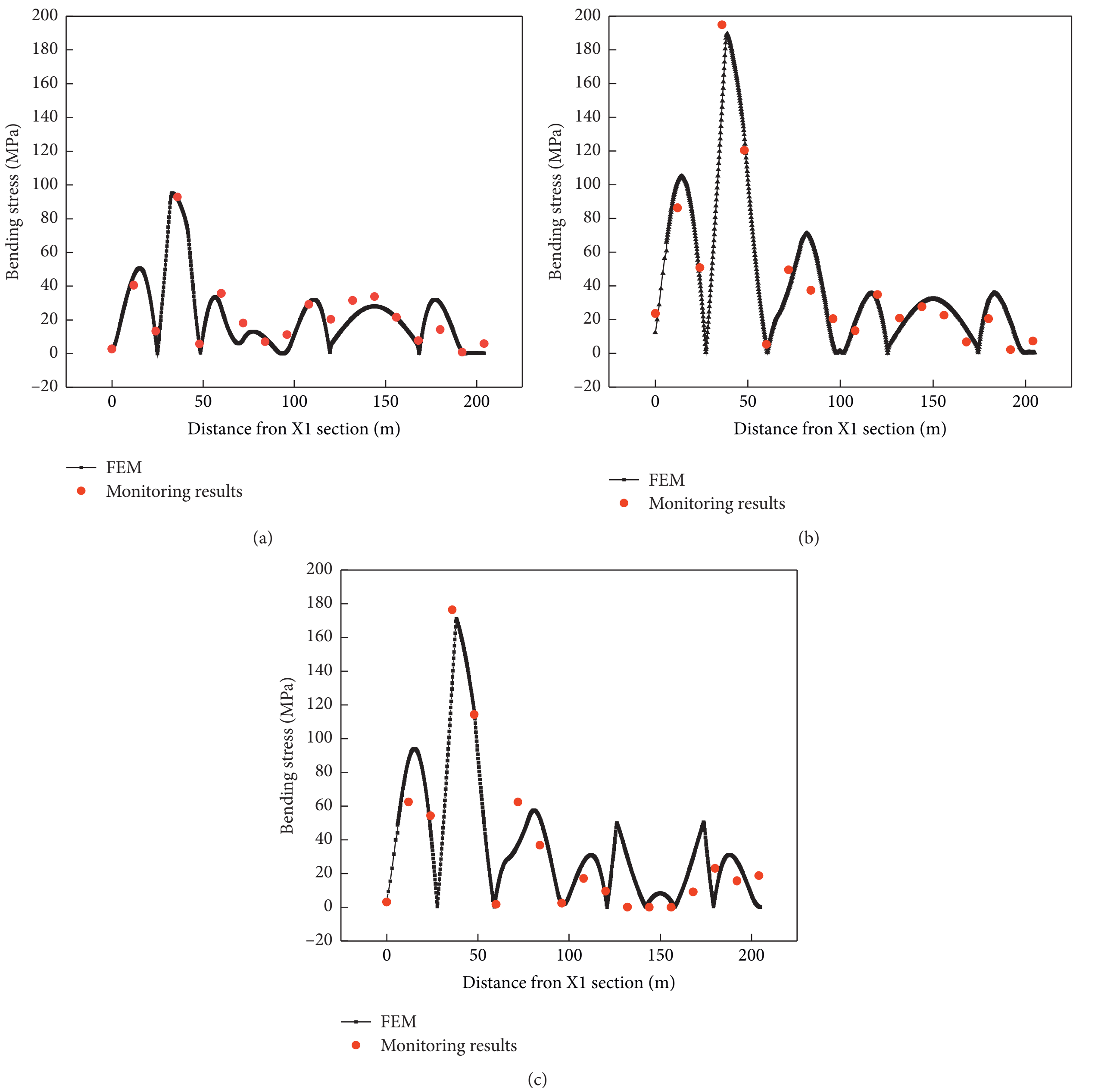


Figure 24: Bending stress of pipeline versus distance from X1 section for various years. (a) X1-X18 section (2014/11/19). (b) X1-X18 section (2017/3/17). (c) X1-X18 section (2018/2/22).

Table 3: Performance of the proposed multidata-based numerical model.

Date	R^2	MAE	RMSE
2014/11/19	0.882	5.77	7.60
2017/3/17	0.875	12.13	16.46
2018/2/22	0.850	13.55	17.80

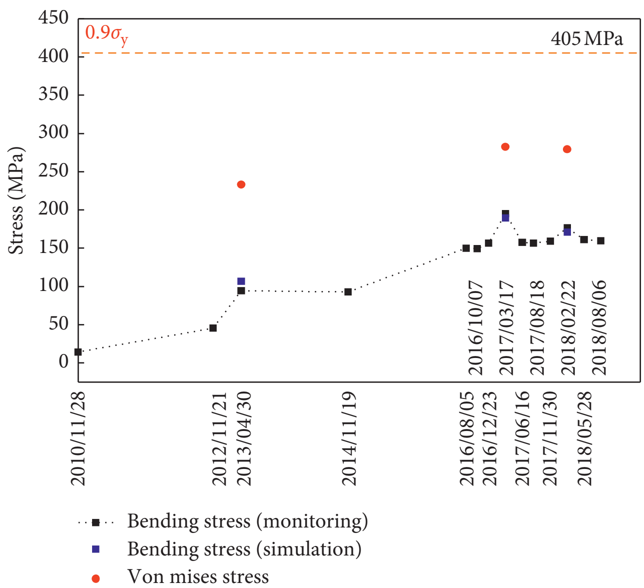


Figure 25: Variation of peak stress in pipe from 2010 to 2018.

5. Conclusions

Stress analysis of the buried heated oil pipeline crossing permafrost areas via multisource monitoring data-based numerical method was studied in this paper. Taking one heated pipeline in northeastern China as prototype, a general coupling data analysis procedure was proposed. Results show that based on the pipe soil interaction model assumed according to monitoring data, the pipe's overall stress state in the geohazard area can be more accurately obtained, which fills the gap that monitoring data can only reflect the monitored pipe section's mechanical states. Based on the investigation, some remarkable conclusions can be drawn as follows:

(1) IMU bending strain results and strain gauge-based longitudinal strain results both can reflect pipe's mechanical states to some extent. Consistent peak stress and strain results and distributions were found by these monitoring methods in the considered case in the presented paper.

(2) Nonlinear soil springs-based pipe soil interaction model with reasonable soil parameters can reflect pipe's mechanical loading induced by frozen soils, as quite small error was found between the proposed numerical model and the filed monitoring results.

(3) The proposed method can reveal pipe's actual stress state precisely. For the considered X65 pipeline, three years' numerical results show that the maximum relative error of pipe's peak bending stress is less than 15%.

(4) For the investigated pipeline, the peak stress was found based on the proposed method is located at section X4. The peak bending stress in pipe increased from 10 MPa to 149.5 MPa during 2010 to 2016. The vertical strain of this section achieved the maximum value of 0.73% in 2016. After 2016, the thawing settlement in this area becomes stable, and only small stress variations appear in the pipe due to the seasonal temperature change.

(5) Based on the application results, it can be found that safety assessment of buried heated oil pipeline crossing permafrost areas can be evaluated more quantitatively based on the established model.

(6) The proposed coupling data analysis method can also be referred in stress/strain analysis of buried pipeline crossing other types of geohazards, such as mining subsidence regions and landslide regions. Based on the multisource monitoring data of pipeline, the possible geohazard types faced by the pipe and assumed initial surface displacement can be determined, which can be used for the establishment of numerical inversion model. The comparative analysis of simulation results and monitoring results was adopted to verify the reliability of the inversion results. Based on the relatively accurate inversion model, assessment of pipeline safety status subjected to geological hazard was conducted.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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