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Review Article

Stability of the Foundation of Buried Energy Pipeline in Permafrost Region

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During operation, a buried pipeline is threatened by a variety of geological hazards, particularly in permafrost regions, where freezing-thawing disasters have a significant influence on the integrity and safety of the buried pipelines. The topographical environmental conditions along the pipeline, as well as the influence of frost heave and thaw settlement on the pipeline's foundation soil, must be considered in the design and construction stage. Theoretical analysis, numerical modeling, field testing, and mitigation measures on vital energy pipelines in permafrost have been widely documented, but no attempt has been made to review the freezing-thawing disasters, current research methodologies, and mitigation strategies. This article reviews the formation mechanisms and mitigation measures for frost hazards (e.g., differential frost heave, thaw settlement, slope instability, frost mounds, icing, river ice scouring, and pipeline floating) along buried pipelines in permafrost regions and summarizes and prospects the major progress in the research on mechanisms, analysis methods, model test, and field monitoring based on publications of studies of key energy pipelines in permafrost regions. This review will provide scholars with a basic understanding of the challenging freezing-thawing hazards encountered by energy pipelines in permafrost regions, as well as research on the stability and mitigation of pipeline foundation soils plagued by freezing-thawing hazards in permafrost regions under a warming climate and degrading permafrost environment.

1. Introduction

For over a century, the design, construction, and operation of buried energy pipelines have gone on without a break. As the most convenient and economical means of transporting oil and gas from the fields to the communities, buried pipelines are affected by various geological hazards. In particular, for buried pipelines through permafrost regions, the influences of the freezing-thawing hazards on the ambient environment and integrity of the pipeline system are huge; this is not because of melting ice or hazardous soil but of the consequences of ground-ice melting. Under the combined influences of climate warming and heat dissipation from buried pipelines [1], the risks of differential frost heave and thaw settlement of pipeline foundation soils can trigger the ovation, sagging, buckling, and failing of the pipeline, leading to pipeline leakage and devastating environmental disasters [2]. As shown in Figure 1, the buried energy pipelines in the permafrost regions have suffered various degrees of uplifts or settlements. Many methods have been proposed by researchers to assess the interactions between the pipeline and the soil, as well as the mechanisms of the frost hazards along buried pipelines in permafrost regions.

Many crude/product oil and natural gas pipelines have been built in permafrost regions, and Table 1 provides some

Figure 1: Frost hazards along the buried energy pipelines in permafrost regions: (a) uplift of the buried Golmud-Lhasa product oil pipeline above the ground modified by [3]; (b) water pond in thaw subsided ditch along the China-Russia Crude Oil Pipeline (CRCOP) from Mo'he to Daqing, Heilongjiang Province, Northeast China, modified by [4]; (c) bulged uplift of the Norman Wells Pipeline above the ground modified by [5]; (d) thaw settlement along the CRCOP in 2011 modified by [6]; (e) the exposed gas pipeline by landslide in western Siberia modified by [7]; (f) the floating up of the gas gathering system in northern Urengoy, Siberia, modified by [8].

key data for these vital pipelines. Four major pipelines in the world have been more studied in the literature: the Norman Wells Oil Pipeline (NWOP), the Trans-Alaska (Alyeska) Pipeline System (TAPS), the Golmud-Lhasa Oil Pipeline (GLOP), and the China-Russia Crude Oil Pipeline (CRCOP).

The NWOP, constructed in 1972–1977, is the first trunk pipeline buried in the zone of discontinuous permafrost in western Canada. The pipeline is small in diameter (328 mm) using Grade 359 (X52) steel, and the top of the pipe is buried at a depth of about 1.1 m [9]. The oil flow is chilled to near ambient temperatures to prevent large disturbances from pipeline conduction and from convective heat transfer between the buried pipeline and the ambient permafrost soil. However, because of the presence of discontinuous permafrost and dramatic changes in ambient temperature, it still caused ground frost heave or thaw settlement and other geological hazards [10]. The pipeline is once frost upheaval off the ground by about 1.1 m due to the immense axial stress. Some particular approaches, such as gas chilling, layered insulation, and wood chip insulation on unstable slopes from thawing, have been selected to mitigate interactions between the pipeline and foundation soils and thus protect the pipeline from frost hazards [2].

The TAPS is a crude oil pipeline of 1287 km in length and 1.22 m in external diameter; it crosses permafrost regions at a speed of 3.3 m/s, and the oil-flow temperature is 38 to 63°C [11]. To protect permafrost from thawing, approximately 700 km of the pipeline are elevated above the ground and supported with thermosyphon-cooled posts (vertical support beams) to prevent heat from being conducted into the soil. The pipeline is bound up with 10 cm thick fiberglass insulation to protect the permafrost from excessive thermal disturbances [12].

Table 1: Features of main energy pipelines in permafrost regions.

Pipelines (references)	Routing	Construction (year and season)	Pipe diameter (mm)	Length (km)	Burial depth (m)	Comments
Trans-Alaska Pipeline System (TAPS) [25, 26]	Valdez-Prudhoe Bay, Alaska, USA	1973-1977 Winter	1220	1287	0.4~4.0	Oil temperature: 38~63°C; oil flow rate: 3.3 m/s; main problem: thaw settlement
Alaska Natural Gas Transportation System [27]	Prudhoe Bay, Alaska, USA, to Alberta, Canada	1981-1986 Winter	1219 (Alaska) 1420 (Canada)	1198 (Alaska) 3271 (Canada)	Above ground	Gas temperature: -17°C; main problems: frost heave/thaw settlement
Golmud-Lhasa Oil Pipeline (GLOP) [15, 28]	Golmud, Qinghai Province, to Lhasa, Tibet Autonomous Region on the Qinghai-Tibet Plateau, China	1972-1977 Winter	159	1078	1.2-1.4	Oil temperature: -5~+9°C; oil flow: 5900 barrels/day; main problems: thaw settlement/frost heave
Norman Wells Oil Pipeline (NWOP) [2, 10]	Norman Wells, Northwest Territories, to Zama, Alberta, Canada	1983-1985 Winter	328/359	869	1.1~1.2	Ambient temperature: -4~12°C; oil temperature: -1~0°C; oil flow: 5000 m^3/day; main problems: settlement/uplift/instability of slope
China-Russia Crude Oil Pipeline (CRCOP) [21, 22]	Skovorodino, Amur Prefecture, Russia, via Mo'he to Daqing, China	2009-2011 (I) 2018 (II) Winter	813	953	1.6~2.0	Ambient temperature: -41~24°C; main problems: thaw settlement/uplift/ instability of slope
ESPO (Eastern Siberia to Pacific Ocean) Oil Pipeline System [29]	Taishet in Irkutsk Oblast to Skovorodino in Amur Oblast, Russia, along with a branch from Skovorodino to Daqing, China (933 km) (I); another branch from Skovorodino to Kozmino Bay (II)	2006, spring (I) 2009 (II)	1220 (I); 1067 (II)	2757 (I); 2100 (II)		Mean annual air temperature: -7~-6°C; main problems: thaw settlement/uplift/ instability of slope
Nadym-Pur-Taz Gas Production Complex (NPT) [8]	Urenoyskoye field in western Siberia to Torzhok, Russia	1995	1020/ 1220/1420	2200	1.5~2.0 (part)	Insulated with polymer tape

The GLOP is a 1078 km long, 159 mm diameter pipeline that runs from Golmud, Qinghai Province, to Lhasa, Tibet Autonomous Region, China, dubbed as the Golmud-Lhasa Oil Pipeline (GLOP). It is built in 1975-1977 in a conventional burial construction mode; about 900 km of the pipeline is at elevations of above 4000 m asl, with the highest point at the Fenghuo Mountain Pass at 5,228 m asl [13–15]. The temperature of the product oil varies seasonally from -5 to +9°C. During the past 43 years, the pipeline has suffered over 30 sizable leaks due to differential frost heave or settlement, earthquakes, periglacial geological hazards, and other unintended damage from construction projects. From 2001 to 2004, about 300 km of pipeline segments of the GLOP were replaced or rerouted to ensure safe operation and integrity [16, 17].

The CRCOP passes through about 1030 km of frozen ground zones to transport crude oil from Skovorodino, Amur Prefecture in Russia, to Daqing, Heilongjiang Province in Northeast China. The Chinese portion begins in Lianyin, Mo'he County, Heilongjiang Province, and extends 933 km southward to Daqing, Heilongjiang Province, of which 441 km is in the zone of discontinuous permafrost and 512 km in the zone of seasonal frost. The CRCOP is 0.813 m in outer diameter and conventionally buried at depths of 1.6-2.0 m [18–20]. The CRCOP I is built in 2008-2010 and operated in January 2011. Eight years afterward, the CRCOP II is built in 2016-2018 and operates until January 2018 in parallel with the CRCOP I 10 m apart. Due to excavation disturbance and heat conduction from the oil pipeline, the hydrothermal equilibrium of the underlying permafrost has changed, in some regions where the surface water replenishment and the intense water and soil erosion have led to substantial pipeline subsidence and thermokarst [21–23]. Meanwhile, frost mounds and aufeis develop widely along the right-of-way along the pipeline route; they can uplift the pipeline, threatening its safety [24]. The CRCOP I and II have suffered frost hazards to various degrees during their service periods, threatening their operational safety and long-term stability.

When a warm or chilled pipeline is buried in permafrost, heat conduction and convection will occur between the pipeline and the ambient soils. The thawing of permafrost substantially reduces the bearing capacity of the foundation soils, and the differential thaw settlements could cause excess stress and strain, leading to pipeline failures. Meanwhile, the frost heave of the foundation soils produces an upward thrust on the pipeline; the weight of the overlying soil over the pipeline cannot effectively resist the upward movement tendency of the pipe; the pipeline may jack up and eventually get out of the ground or buckle. The frost heave of the foundation soils would destabilize or even damage the pipeline due to the excessive deformation of the uplift. Besides, freeze-thaw landslides may cause pipeline exposure and stress concentration, leading to the failure of pipelines due to excessive stress or strain. Other frost hazards may also lead to excessive deformation or internal forces of pipelines, such as landslides, debris flows, erosion, and floating.

The hydrothermal and mechanical stability of the foundation soils of the buried energy pipelines is crucial to the safety of the buried pipelines. This paper reviews the literature on energy pipelines in permafrost regions and the pertinent hydraulic, thermal, and mechanical properties of permafrost soils that affect the stability and operational safety of foundation soils of pipeline mechanics buried in permafrost regions during the last 10 to 15 years, and the geotechnical hazards of buried pipelines, the methods to study the interactions between the pipeline and foundation soil, and the mitigative measures for disasters are summarized and prospected.

2. Geotechnical Issues of Buried Energy Pipelines in Permafrost Terrains

The geological conditions in permafrost regions are complex and variable, and the construction and operation of infrastructures affect the water and heat balance of frozen soil; in turn, the safety of infrastructures would also be affected by the change in soil [30, 31]. Permafrost is inevitably disturbed during the construction and operation of the pipeline; heat exchange between the pipeline and the permafrost affects the moisture content of the soil and speeds up the degradation of the underlying permafrost [7, 32]. According to surveys, geological hazards associated with pipeline building and operation/maintenance in permafrost regions affected by frozen ground are mainly differential frost heave and thaw settlement [24]. Figure 2 shows the design process of pipelines in permafrost regions. Geological hazards must be considered, including (differential) frost heave, thaw settlement, slope instability, pingos, gelifluctions, and other periglacial geological hazards [2].

2.1. (Differential) Frost Heave. Frost heave is the phenomenon of ground heave as the water transforms into ice when the fine-grained or frost-susceptible soil is subjected to freezing [33]; it is caused by ice formation from unfrozen water or external resources that migrates to the freezing front [34, 35]. When the temperature gradient is sufficiently large and the freezing front moves rapidly, the pore water freezes in situ, causing volumetric expansion; while the gradient is slight, the freezing front moves slowly, and water migrates from the unfrozen to the frozen areas, forming segregated ice [36].

Frost heave is a complex physical process; theoretical models are needed to analyze it accurately [37, 38]. With the development of numerical methods and continued research on frost heave, various models have been proposed for studying the frost heave mechanisms: (i) capillary theory: Everett [39] proposed a model based on the capillary theory, stating that capillary suction is the main driving force for water migration, and the size of soil particles and pore are important factors for determining frost heave sensitivity. However, the calculated frost heave is less than the measured frost heave, and the formation of the ice lens was not explained; (ii) hydrodynamic model: first proposed by Harlan [40] based on the moisture migration theory of unfrozen soil, it has been developed and evolved for predicting the water migration rate [41–43], but it was not accurate for simulating the amount of frost heave because it did not account for the external force; (iii) segregation potential model proposed by Konrad and Morgenstern [44] assumed that the velocity of pore water entering into the unfrozen soil was proportional to the temperature gradient when the suction at the pore-freezing front was constant [45, 46]. The SP model predicted frost heave from the basic properties of the soil in the one-dimensional model, but it did not consider the surface thermal effect and relied on laboratory tests to determine the parameters of the soil. Additionally, it is no longer applicable to nonsteady thermal conditions [47]; (iv) rigid-ice model [48] put forward by O'Neill and Miller [49] assumed that the ice and soil skeleton were incompressible during the freezing process. It took into account the hydrothermal coupling at the freezing fringe, the pore ice in the frozen fringe zone was closely connected with the growing segregated ice, and the suction force of the soil was greater than that of ice. But the model was also questioned as to whether the freezing edge exists and needs further exploration [50]; (v) hydro-thermo-mechanical model [51–54]: the model described the moisture and heat transport, as well as the suction caused by frost heave, using the principle of continuum mechanics and macroscopic thermodynamics [55, 56]. The thermo-mechanical model only described the microscopic frost heave mechanisms; it did not calculate the amount of frost heave; (vi) premelting dynamic models [34, 57, 58] were also called the thermal molecular force theory; they explained the formation mechanism of an unmoved water film and the driving force of water migration. So far, the theory was still less applied to solving the problem, but it explained the frost heave from a microscopic point of view. Although a large amount of research has been conducted on the frost heave model, the general model has not reached a consensus.

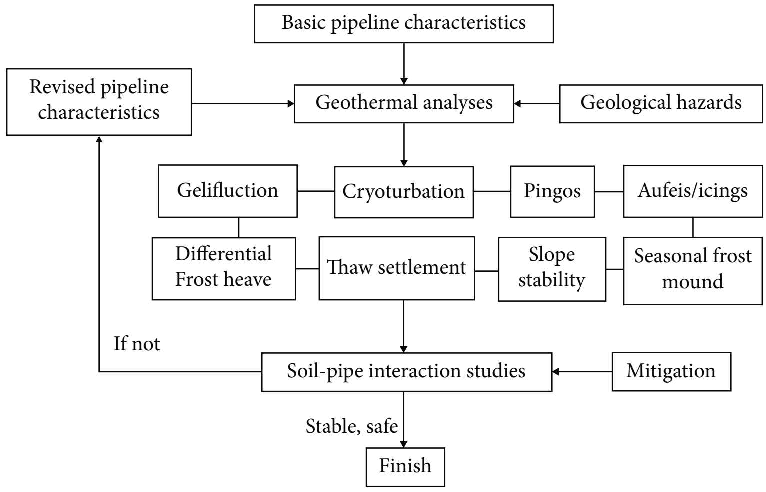

Figure 2: Flowchart of geotechnical input to cold region pipeline design modified by [2].

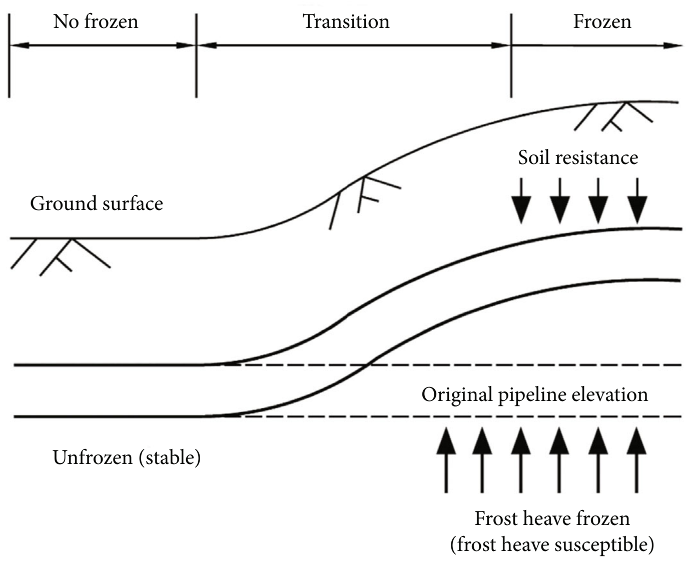

Figure 3: Differential frost heave along a pipeline.

Several chilled pipelines have been buried in permafrost to transport natural gas. The advantage of the buried chilled pipeline is that it can protect the permafrost from thawing and enhance buoyancy. However, in the unfrozen zones (such as talik), the main problem is that it could cause the frost-susceptible soils around the pipeline to freeze, uplifting the pipeline [47, 59, 60]. As shown in Figure 3, the differential heave caused by soil freezing with different susceptibilities or between frozen and unfrozen regions results in the stress and strain of the pipeline which are maximum at the boundary section of the pipeline. Therefore, for the chilled gas pipelines, Konrad and Morgenstern [45] proposed two critical questions: how much frost heave would occur during the lifetime of the pipeline, and how much differential frost heave would occur in the design and construction of the pipelines?

2.2. (Differential) Thaw Settlement. Due to the unique physical properties of the permafrost, climate warming and disturbance would deepen the active layer and induce the permafrost to thaw; the construction and operation inevitably disturb and thaw the underlying permafrost [61, 62]. For pipelines in permafrost regions, vegetation clearance and trench excavation alter the thermal conditions of the underlying permafrost, causing frozen soil to thaw. If the thaw settlement of the foundation soils developed evenly, the pipeline would have little or no impact. However, the lithological and topographical conditions of the soil around the pipeline are not the same; under the heating influence of the pipeline, the surrounding soil will undergo differential settlement, resulting in the bending of the pipeline [63], as shown in Figure 4. For example, when the NWOP traversed the frost-thaw sensitive areas, because of the high oil temperature, severe thawing of the pipeline foundation soil caused the pipeline to experience significant settlement [33, 64]. The CRCOP was also affected by the warm oil, thawing around the pipeline was significant, it can be seen from the

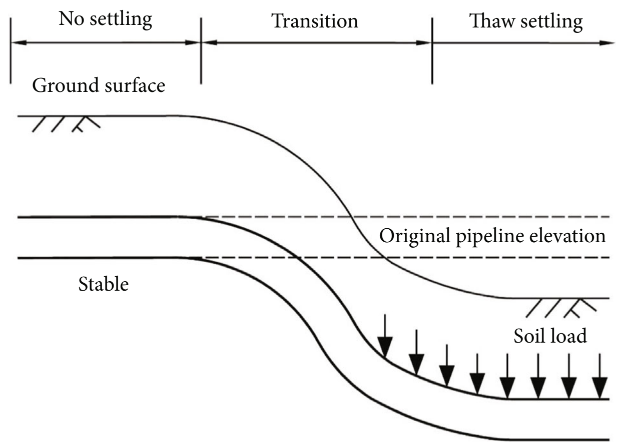

Figure 4: Chart for different thaw settlements along the pipeline.

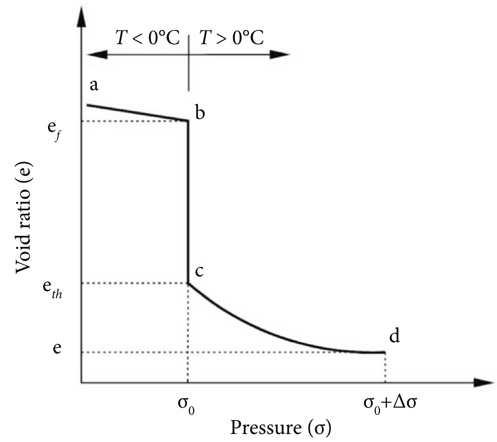

Figure 5: Typical void ratio versus pressure curve for frozen soils subjected to thawing [67].

field monitoring data that the permafrost table around the pipeline was greater than the natural ground, and the thaw bulb around the pipe developed faster [65]. With the operation of the warm pipeline, the range of permafrost thawing and thaw bulb around the pipeline expands, causing ground settlement within the trench of the pipeline. Then, in the warm season, surface runoff, rainfall, and groundwater converge in the trench depression, which will accelerate the degradation of permafrost and the development of the thawing bulb around the pipeline.

In addition to the influence of pipeline temperature, climate warming also affects the pipeline. Climate warming has led to the degradation of frozen soil and the thawing of pipe foundation soil in permafrost regions. Under the background of global warming, the permafrost degeneration, the thickening of the active layer, and the rise in ground temperature will aggravate the thawing disaster of the pipeline. At the same time, the vegetation cleaning during the pipeline construction will also cause the excavation of the trenches. The pipe soil is subject to greater thermal disturbance. The thaw settlement of the permafrost soil needs to be evaluated to determine the stresses imposed on the pipeline, and the extent of permafrost thaw under and around the pipeline is vital to the design and construction modes of the pipeline. It is also critical to assess the impacts of the pipeline on the surrounding permafrost environment.

The relationship between void ratio and pressure in the thaw settlement test is shown in Figure 5. The permafrost soil thaws, the void ratio drops quickly due to ice change in the water, and the excess water drains out of the soil. The consolidation of foundation soil causes the pipeline to suspend; the stress and strain of the pipeline increase under the gravity and earth pressure. The pressure σ_0 is decided by the effective overburden pressure of the field sample [66]. The magnitude of thaw settlement directly depends on the ice content and the degree of disturbance, and it is the sum of the thaw deformation under gravity and the consolidation deformation under external load.

For pipelines in permafrost, besides frost heave and thaw settlement, the differential thaw settlement or frost heave of pipe foundation soils in the transition zone between permafrost and talik should also be considered. As a buffer, the transition zone lies between the permafrost and the talik. It has an ice-rich, warm, and high content of unfrozen water, great viscoplasticity, and rheological properties that are inconsistent with permafrost and talik and somewhere in between [68]. According to the field test data, Gao et al. [69] calculated the reasonable length of the frosting-thawing embankment transition zone of the Tuotuo River section along the Qinghai-Tibet Railway within three years after completion. The transition zone is sensitive to temperature change; the disturbances in construction and operation would affect the stability of foundation soils. Uneven frost heave and thaw settlement of the transition zone would significantly affect the internal force and deformation of the transition section pipeline. Thus, reasonable section length and measures should be taken to ensure the safe operation of the pipeline.

2.3. Slope Instability. Natural slopes in permafrost terrains could become unstable under geological conditions, climate change, human activities, and other factors. Simultaneously, pipeline construction and thermal influences would change the moisture and heat balance of the permafrost slope and cause landslides that severely impact the safe operation of energy pipelines. The stability of permafrost slopes may be enhanced when the chilled pipelines have a cooling effect on the foundation soil; however, in unfrozen areas, the formation of a frost bulb around the pipe affects the drainage of the foundation soil, which may destabilize the slope [70]. Landslide in the permafrost region is mainly characteristic of thaw slumping or active layer detachment failure. It is a critical factor affecting the integrity of the pipeline. Slope stability is affected by climate change and the thermal disturbance of the pipeline buried in permafrost. This instability depends on the reduction in the shear strength of the slope, which is affected by the water and ice content of the slope's thawing soil [71–74]. If the force of the landslide that is exerted on the pipeline exceeds the allowable value, the pipeline will suffer great stress and excess deformation. Under the action of internal pressure, some parts of the pipeline

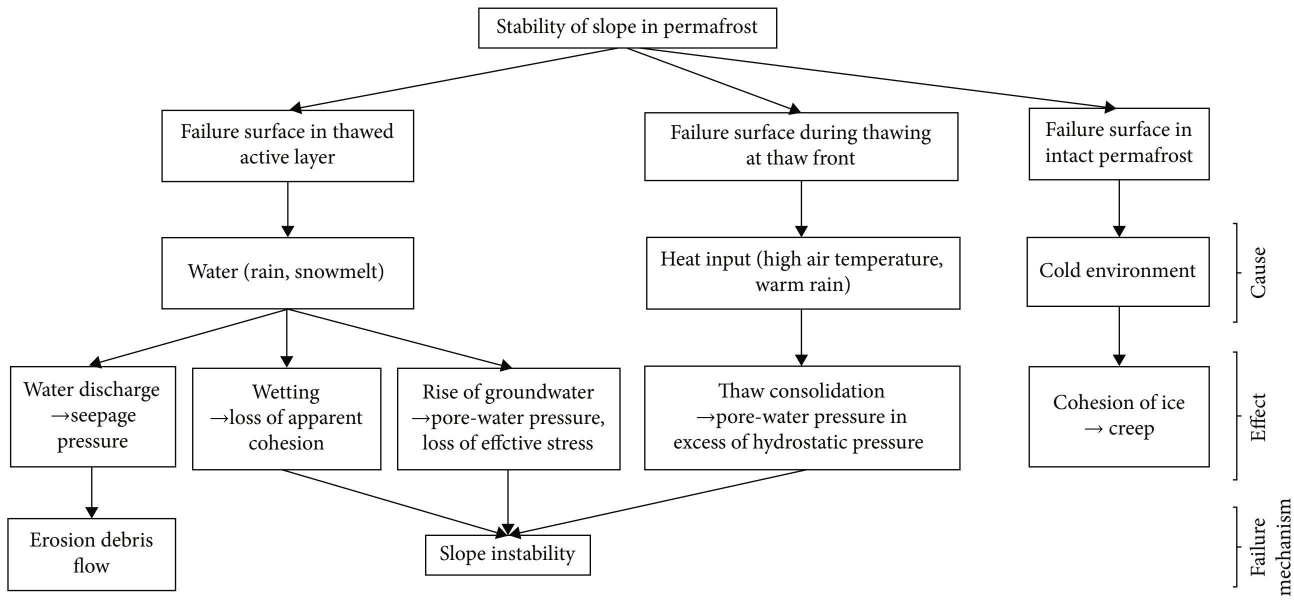

Figure 6: Possible causes, effects, and failure mechanisms of slopes in permafrost environments [75].

produce an apparent stress concentration, leading to plastic yield, even rupture, and causing significant accidents, such as oil and gas leakage and detonation. The stability of the slope is affected by many factors, such as moisture content, ice content, soil properties, slope angle, and length. Figure 6 shows the potential causes, effects, stability, and failure mechanisms of the permafrost slopes.

Active layer detachment (ALD) failures are shallow translational landslides that develop on gentle slopes in thawing soil over permafrost; the failure surfaces of the landslides are parallel to the ground surface [76–78]. The ALD landslides are triggered by the high excess pore water and low effective strengths due to the rapid melt of the ice lenses near the active layer-permafrost interface in summer when the temperature rises [79, 80]. If the pipeline crosses the ALD landslide area, the buried pipeline changes the hydrothermal of the active layer to accelerate the landslide; the landslide affects the stress and deformation of the pipeline [81]. Under the influence of pipeline-soil interactions, the pipe bends and may induce plastic instability, or even fracture.

Currently, there are many unilateral studies on landslides and pipelines in permafrost areas, but few studies on the instability mechanisms of pipeline landslides. Some literature attributes the instability of permafrost slopes to excess pore water pressure. Figure 7 presents a case in which excess pore water pressure changes with time in the process of ground thawing. Excess pore water pressure could degrade slope shear strength, increase slope instability, and affect pipeline safety, so thaw-induced slope instability along the pipeline in frozen terrain must be considered. Bommer et al. [75] applied two case studies to prove that the parallel seepage contributes much more than thaw consolidation to the excess pore water pressures of the slope instability. Qi et al. [82] and Zeitoun and Wakshal [83] proposed a three-dimensional thaw consolidation theory, which could establish an approximation for the thaw of permafrost with relatively low soil moisture content. Rivière et al. [84] experimented with monitoring the pore water pressure change in the freeze-thaw cycles.

2.4. Other Secondary Periglacial Hazards. In permafrost regions, in addition to slope instability and differential frost heave and thaw settlement, other factors may affect the hydrothermal and mechanical stability of the foundation soils of buried pipelines, such as frost mounds, icing, river ice scouring, and pipeline floating.

Frost mounds are common periglacial landforms in polar regions [85], formed by the volumetric expansion of the freezing water in the stratum and containing an ice-core amount or ice-rich frozen cores, and can reach tens of meters in high [86]. If the frost mound is located to the side or below the pipeline, the frost mound's development will squeeze or uplift the pipeline, causing it to bend and endanger the pipeline's safety [87]. For the thermal stability of pipeline foundation soil, measures should be taken to mitigate the effect of the frost mounds on the pipeline, including drilling to discharge water and decompression, building the intercepting drain or intercepting wall, and insulating blind ditch. Drilling to discharge water and decompression can reduce internal pressure and inhibit the development of frost mounds; moreover, the intercepting drain can change the direction of the groundwater flow away from the pipeline [4].

Aufeis (icing) is formed by water flowing from the ice-covered channel under pressure in the river or stream, then freezing; generally, there are spring and river icings [88, 89]. If there is a large-scale aufeis near the pipeline, the development of the aufeis will squeeze the pipeline in winter, while the melting will cause uneven settlement of the pipeline in summer. Similar to the mitigation of frost mounds, measures to mitigate the effects of icing include drilling to release water, reducing pressure, and the construction of water-retaining or drainage facilities. The huge icing near the

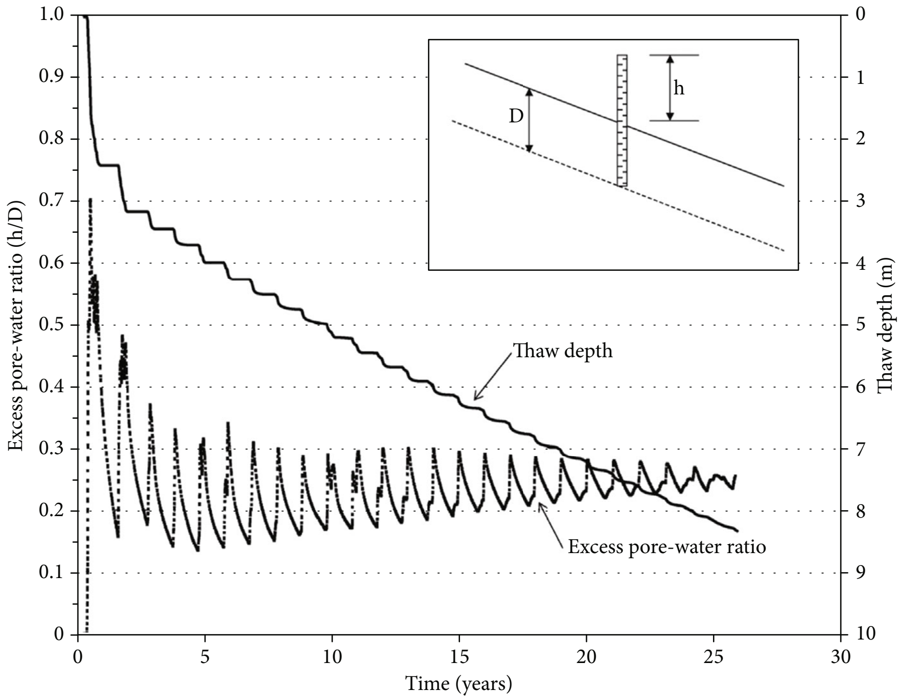

FIGURE 7: Excess pore water pressure and thaw depth with time as a result of thawing permafrost [2].

pipeline can be drilled to decompress, building drainage ditches or diaphragm walls upstream of the icing to change the direction of flow paths away from the pipeline.

Ice scouring or gouging is the phenomenon whereby ice floes or icebergs flow downward with the current, while the icebergs will form a gouging effect on the shallow riverbed or the bottom of the ocean in the process of flow. When the pipeline crosses rivers or seas in permafrost regions, such gouging action will squeeze or drag the pipeline buried in the riverbed or the seabed, move or expose the pipeline, and even cause the pipeline to bend and break when the deformation is large [90, 91]. To avoid the threat of ice scouring to the pipeline, the most direct and straightforward measure is to bury the pipeline below the line of ice scouring.

For buried pipelines, especially gas pipelines crossing rivers or streams in permafrost regions, they will be exposed and floated when the buried depth is relatively shallow while the water flow is large or meets an extensive flood in summer. The floating pipeline may be bent and damaged by vibration fatigue under the flow impact, even rupture [92]. Mitigative measures for pipeline floating include increasing the burial depth of the pipeline, laying gabions at the bottom of the riverbed to increase the erosion resistance of the riverbed, and increasing the floating pressure of the pipeline.

3. Pipeline-Soil Interactions

Under the influence of climate warming and pipeline activities, the permafrost environment on the right-of-way (ROW) and near the pipeline corridor would be affected, resulting in (differential) thaw settlement and/or frost heaving of the foundation soils and other frost and geological hazards, which can affect the safety and integrity of the energy pipelines. Heat transfer between the pipeline and surrounding soils affects water migration and subsequent ice formation in the foundation soils and accelerates changes in permafrost and talik in surrounding areas. The sidewall and bottom of the pipeline may compress the surrounding soil, while the soil also produces elastic resistance to restrict the movement of the pipeline. Therefore, when studying the interactions of buried pipelines with the permafrost environment, the soil within a specific range of the pipeline must be taken into account.

Geological hazards in permafrost regions along buried pipelines are more complicated than those of other regions; researchers have adopted many methods to investigate the mechanisms of pipeline-soil interactions [33, 93–100]. Selvadurai et al. [100] developed a three-dimensional computational model that considers the heat conduction and moisture transport coupling processes to study the pipeline-soil interactions during the frost heave process in frozen soil. Hawlader et al. [94] put forward a semianalytical solution to investigate the pipeline-soil interactions and frost heave deformation, yielding consistent numerical predictions. Wei et al. [101] proposed a 3D model to analyze the pipeline-soil interaction of the warm pipeline crossing fault in permafrost. Huang et al. [95] established a pipeline-soil interaction model based on the theory of elastic foundation beam to study the stress distribution of the pipeline under the action of frost heave. Wang et al. [30] performed a test to study the interfacial stress between the frozen sand and the pipeline; the results showed a much larger interfacial stress at a frozen state than at room temperature. Meidani et al. [102] presented a three-dimensional discrete model to analyze the response of the buried pipeline that undergoes axial ground movement and used experimental data to validate the results. Interactions between the pipeline and frozen/thawed soil must be considered in pipeline design, construction, and operation, and integrated numerical modeling of the pipeline in both frozen and unfrozen sections is required.

3.1. Multiphysical Field Coupling. Due to temperature changes or other thermal disturbances, freezing or thawing of pore water would cause complex and interactive thermal, hydraulic, and mechanical processes in the freezing, thawing, and thawed soils. For example, the change in the phase of ice and water in the freezing and frozen soil will alter the hydraulic state of the soil, resulting in soil deformation. Simultaneously, hydraulic processes alter the soil's thermal state by heat transfer, while mechanical conditions affect the hydraulic regimes of the soil by bulk strain. The mechanisms of the thermo-hydro-mechanical (THM) coupling process under freezing or thawing conditions are illustrated in Figure 8. The THM interactions are the major causes of (differential) frost heave and thaw settlement of pipeline foundation soils in permafrost regions.

The THM models of frozen soil began with the initial empirical and semiempirical formulas, which have now developed more maturely and have been applied extensively. [40] first proposed the concept of hydrothermal coupling. Afterward, many hydrothermal coupling analyses have been carried out and applied to solving the problems in permafrost regions [52, 103–110]. Prior research of fully THM coupled modeling of frozen soil proposed by Mu and Ladanyi [107] assumed that the soil was isotropic and had consolidated before freezing, and the simulated temperature results agreed well with the experimental data. Neaupane et al. [108] applied a THM coupling model to simulate the freezing and thawing processes of rock in permafrost regions within an elastic linear limit; the results can predict rock temperature and deformation. Afterwards, Neaupane and Yamabe [109] extended the linear elastic to a nonlinear elastoplastic coupled model to simulate the freezing and thawing of rock; the model can also well analyze the rock moisture and temperature fields under freezing and thawing states. Taking into account the latent heat of the ice-water phase change, Li et al. [106] proposed a heat-moisture-deformation (HMD) coupling model for analyzing the frozen foundation soils. Compared with the pipeline frost-heave test for accurate simulations of the pipeline temperature and moisture fields, Nishimura et al. [110] presented a THM model for studying the freezing and thawing processes in a water-saturated soil and verified its accuracy. Liu and Yu [53] introduced a multiphysical model to simulate the THM coupling process in unsaturated frozen soil and simulated a pavement in a frozen area; the result matched well with the field monitoring data, implying the capability of the model to capture the coupling characteristics. Kang et al. [105] applied the THM coupling model to study rock under freezing/thawing and then simulated the test of a gas storage facility; the results were in good agreement with the field test. Zhang et al. [111] put forward the dynamic thermal-hydro-salt-mechanical (THSM) model of saturated frozen sulfate soil. Research on frozen soil THM coupling is of great significance for solving the engineering problems of buried pipelines in permafrost terrain. However, there are still many unresolved issues, such as the coupling models have not reached the real coupling and there are also certain differences between the computational and actual conditions. Thus, more systematic research is badly needed to solve practical coupling problems in permafrost regions.

3.2. Field Observations and Monitoring. With the rapid development of buried energy pipelines and the aging of existing pipelines, pipeline accidents have occurred more frequently, causing severe ecological damage and substantial economic loss. In particular, in permafrost regions, where the geological conditions and atmospheric environment are complex and variable, intricate interactions occur between the pipeline and frozen soil. Due to the lack of monitoring measures and warning systems for geological hazards and damage in the ROW along the Golmud-Lhasa Pipeline (GLOP), the leakage accidents of the pipeline have caused severe environmental pollution and heavy economic losses [17]. Therefore, it is necessary to establish a field observation and monitoring system along the pipeline for its safe operation and hazard warning for critical pipeline segments. Observations refer to inspecting changes in elevation of the ground surface and pipelines in permafrost regions, such as those through level surveys; it also involves geophysical surveys, such as ground-penetrating radar (GRP), electrical resistivity tomography (ERT), and electromagnet (EM) that provide essential ground-truthing of the pipeline and permafrost conditions [112]. The monitoring programs along the pipelines in the permafrost regions include real-time monitoring of the pipeline operation impacts on the surrounding environment and the pipe-soil interactions [10]. The monitoring of the surrounding environment includes dynamic changes in groundwater level, runoff, ground surface temperature, precipitation, snow cover, and wind conditions. Simultaneously, monitoring of pipe-soil interactions involves temperature indicators in the ROW, changes in frost heave and thaw settlement of the pipe foundation soil, and pipe deformation. The long-term record of ground temperature in the undisturbed area can provide background information on the permafrost environment under a changing climate. At the same time, the record of the right-of-way (ROW) can indicate the thermal influence of the pipeline on the frozen foundation soil. Oil temperature data is essential to understand the thermal interaction between the pipeline and the surrounding soil.

For important pipelines, such as the NWOP, TAPS, CRCOP, ESPO, and Nadym-Pur-Taz Gas Pipeline [8, 21, 64, 113, 114], monitoring systems have been established to observe and study the mechanical and hydrothermal conditions of the pipeline and foundation soils.

To better assess the impacts of the pipeline on the permafrost and the effectiveness of the mitigation measures of NWOP, the permafrost and terrain research and monitoring (PTRM) programs were implemented in cooperation with the pipeline operating company and government departments [10]. The PTRM program recorded data for long-term ground temperature in and out of the ROW, assessing

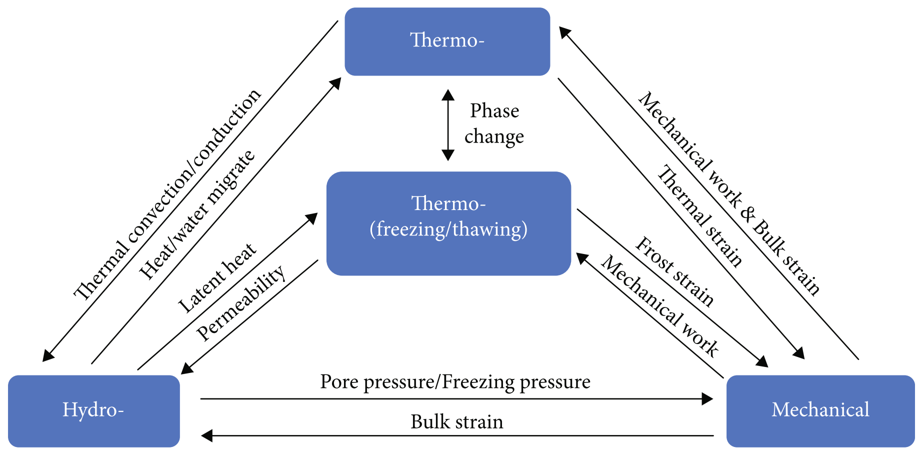

FIGURE 8: Schematic of thermo-hydro-mechanical (THM) coupling under freezing and thawing conditions.

the depth of thaw, the effectiveness of mitigation measures, and climate change. Smith and Burgess [64] introduced the two sites along the NWOP with documented ground and pipe movements since the 1990s; the observation results showed a thaw settlement of about 0.3 m resulting from the increasing thaw penetration. For the CRCOP, the field monitoring system was built along the pipeline, including four monitoring sites, two automatic climate stations, and 30 ground temperature boreholes. Wang et al. [22] described the monitoring sites that recorded the ground temperature, the water content of the foundation soils, oil temperature, subsidence of the ground surface above the pipeline, and thaw bulb around the pipe and evaluated the effectiveness of thermosyphon measures through this monitoring data. Wang et al. [87] used ground penetration radar (GRP) to investigate the thermal state of the pipeline foundations. Li et al. [18] confirmed the effectiveness of thermosyphons using measured soil temperature and water content data. Mu et al. [21] studied the air and soil temperatures at the selected sites along the CRCOP from 2011 to 2107 and investigated the thermal interactions between the pipeline and the foundation soils and the validity of the new design for mitigative measures. Since the operation of TAPS in 1977, many different techniques have been used to monitor pipeline curvatures, such as the inspection device, the monitoring rods, and the advanced internal inspection device "Geopig." Geopig can provide elevation, vertical curvature, horizontal profiles, the location of girth welds, and the ovality of the pipeline [114]. Measurement sites were also set up along the Nadym-Pur-Taz Gas Pipeline to monitor the temperature and surface deformation [8]. For pipelines buried in permafrost, identifying the mode of interaction between the pipeline and permafrost requires data analysis from long-term field observation and monitoring. Thus, long-term sequencing and systematic observation and monitoring systems have important guiding significance for the designing and building of pipelines in permafrost [16, 115].

In addition to field monitoring and observation, the digital surveillance methods, including earth remote sensing (RS), global positioning system (GPS), and geographical information system (GIS) technology, are also effective in investigating geological and geocryological conditions and monitoring the surface displacement of the pipelines [116]. The field monitoring and observation around the pipeline cannot reflect the geological conditions beyond the ROW, while airborne geophysical methods using an unmanned aerial vehicle (UAV) or high-resolution satellites and GIS technology can monitor the status of the pipeline in the remote area at all-weather conditions. It can also detect changes in the deformation of the ground surface above pipelines and in the surrounding environment from small- to large-scale dimensions. For example, the early RS was taken to survey the Alyeska Pipeline in 1973-1974 [117]. Integration of field monitoring and observation with RS technology can provide a more reliable guarantee for the safe operation of pipelines in permafrost regions.

3.3. Model Tests. Based on the mechanical performance and geometric structure of the prototype pipeline, the experimental model was established according to the basic principles of similitude theory, which has all or part of the characteristics of the prototype pipeline structure. The results of the model test can infer the performance of the prototype pipeline and the heave or settlement behaviors of the soil through testing. Several researchers have conducted large- and small-scale models, as well as centrifuge models, to investigate the interactions between the buried pipeline and permafrost soil, as well as to assess the effectiveness of the mitigative measures. The key features of the experiments are summarized and shown in Table 2.

There are three key large-scale chilled pipeline experiments for studying the effects of differential frost heave on the pipeline, including the Calgary frost heave experiment [118], the Caen frost heave test [100], and the Fairbanks frost heave experiment [7, 119]. The Calgary frost heave test facility, located in Calgary, Canada, was constructed to investigate the behavior of the chilled large-diameter pipeline in permafrost and to validate the effectiveness of mitigative measures. The Caen frost heave test was conducted in Caen, France, one-half of the pipeline was buried in unfroze-susceptible soil, and the other half was in highly frost-susceptible soil. The experiment had two stages; the

Table 2: Summary of the main experiments of the chilled and warm buried energy pipelines in permafrost regions.

No.	Pipeline experiment Reference	Model scale	Test time	Operation temperature	Diameter (mm)	Length (m)	Wall thickness (mm)	Burial depth (m)	Comments
1	Calgary frost heave experiment [45, 118]	Large-scale	1974	-10~-7°C	122	12.2	10	0.7	Buried in unfrozen soil with high frost susceptibility; with 15 mm insulation
2	Caen frost heave test [48, 100]	Large-scale	1981	Stage I: -2°C Stage II: -5°C	273	18	5	0.33	Half is located in unfrost susceptible sand and a half in frost susceptible silt
3	Fairbanks frost heave experiment [7, 45, 119]	Full-scale	1999	-10°C	90	105	8.5	1.8	The first 30 m of the pipeline is in permafrost and the rest are in talik
4	Inuvik pipeline experiment [120, 121]	Large-scale	1971	71°C	610	27	1.25	1.5	Warm oil pipeline buried in ice-rich permafrost; operated for six months
5	Small-scale pipeline experiment based on the CRCOP [122]	Middle-scale	2010	-15~25°C	108	7.8	4.5	0.25	Two parallel pipelines, one is insulated and the other is bare
6	Centrifuge modeling of Calgary frost heave [123]	Small-scale	2002	-10°C	41.3 (test 1, 2) 22 (test 3)	0.7	1.59	0.25 (test 1) 0.57 (test 2)	Centrifuge acceleration: 30 g (test 1), 50 g (test 2), and 55 g (test 3) Test time: 5.5 and 6.25 h
7	Centrifuge model of warm oil pipeline [124]	Small-scale	2018	Warm: 7°C Cold: 2°C	11.1	0.27	0.25		Air temperature: -16.83~19.7°C; oil temperature: 2~6°C; two warm pipelines were buried; centrifuge acceleration: 8 g

first stage of the test was conducted to examine the behavior of the pipeline at the intersection of two initial unfrozen soils of different frost heave susceptibilities. The second stage was designed to study the behavior of the chilled pipeline in the transition zone from frozen to unfrozen soils.

The University of Alaska Fairbanks (UAF), Fairbanks, Alaska, USA, and Hokkaido University, Japan, cooperated in conducting a pipeline experiment to analyze the deformations and induced strain of the chilled pipeline in the zone of discontinuous permafrost. The experiment reported three-year monitoring data on frost heave characteristics; the maximum uplift was about 0.197 m near the thermal boundary, resulting in a differential frost heave of 0.148 m [45, 119, 125]. In addition to full-scale experiments, some laboratory experiments are conducted to study the mechanisms for warm pipeline permafrost interactions, which are similar to the Inuvik warm pipeline experiment and the model test base on the China-Russia Crude Oil Pipeline. Since the strength and stiffness of soil are determined by effective stress, the small-scale pipeline models under gravity cannot accurately reflect the behavior of the actual pipeline, so researchers proposed centrifuge modeling to study the pipeline's behaviors [124, 126, 127]. Centrifuge geotechnical tests put the small-scale model in a high-speed rotating centrifuge, allowing the model to bear the effect of centrifugal acceleration greater than the acceleration of gravity to compensate for the loss of weight caused by the reduction of the model size. Centrifugal technology has been proven to be effective for gravity-related tests. The typical model is the Canada C-CORE test; Clark and Phillips [123] operated to simulate the Calgary frost heave experiment; the results were in good agreement with the Calgary frost heave test. Li et al. [124] conducted a centrifuge test of the buried pipeline in the C-CORE laboratory in Canada to confirm the effectiveness of the thermosyphon cooled sandbag mitigation applied to the China-Russia Crude Oil Pipeline (CRCOP). Many factors affect the interactions between the pipeline and permafrost, in the natural environment; the interactions are much more complicated than those in the model test. The model cannot accurately predict the force and deformation of the pipeline-soil system, but it can provide mechanical characteristics and an experimental foundation for studying the buried pipeline in the permafrost area.

4. Mitigative Measures

The construction and operation of the oil and gas pipeline would affect the heat and water condition of the permafrost, which could lead to changes in the thermal stability of the pipe foundation soil, posing a threat to the safe operation of the pipeline. Therefore, it is necessary to take mitigative measures to protect the safety of pipelines in permafrost regions. The crucial measures are

(1) designing an optimized route based on the geological survey data and improving pipe performance. The best approach is to optimize route selection based on the geological survey and other comprehensive analyses to avoid areas with freezing-thawing hazards. From the standpoint of geotechnical engineering, the pipeline route should avoid thick ground ice and frost mounds by choosing an area with low moisture content, aridity, deep groundwater, and high coarse particle content [4]. In the meantime, the pipeline route should keep a certain distance from the existing roads and railways to avoid mutual hydrothermal influences. Increasing the wall thickness or the steel grade of the pipeline during the design stage can significantly improve the pipeline's ability to resist deformation and damage and improve the pipeline's adaptability to the freezing and thawing deformation of the foundation soil. For example, the general wall thickness of the China-Russia Crude Oil Pipeline is 11.9 mm, while in the sensitive areas of frost heave and thaw settlement, the wall thickness is up to 17.5 mm [65]

(2) modifying the laying methods to reduce the disturbance to the permafrost. The construction of buried pipelines will first destroy the vegetation on the surface and reduce the insulation effect of vegetation on permafrost. At the same time, the excavation of the pipe trench will directly damage the permafrost, and it may change the surface runoff and groundwater, resulting in the accumulation of water in the excavation trench and accelerating the degradation of the permafrost. Therefore, if the pipeline laying method is buried, it is necessary to minimize the effect of the construction and carry out vegetation removal and construction in winter. For example, during the construction of the second line of the China-Russia Crude Oil Pipeline, in order to reduce the impact of the removal of vegetation along the pipeline right-of-way on the permafrost, a parallel to the first line was adopted, and overexcavation was carried out in the poor frozen soil engineering geology section [20, 65]. In addition, another method of laying pipelines in permafrost regions is overhead. The Trans-Alaska Pipeline System adopted the laying method of the heat pipe overhead pipeline laying method to reduce the disturbance of the high-temperature pipeline to the permafrost, thereby reducing the suffering of the pipeline from frost heave, thawing settlement, and seismic faults, which have a great impact on the stress and strain on the pipeline [12]. So, in permafrost regions, the most effective way to lay a pipeline is overhead, which can avoid disturbance to the frozen soil and ensure the safety of pipeline operation, but its cost is high and it is not conducive to forest fire prevention

(3) wrapping the pipeline with an insulation layer. The insulation material has low thermal conductivity, which can effectively reduce the heat transfer between the frozen soil and the pipeline and protect the permafrost. The insulation method is an effective antifreezing and thawing measure in permafrost regions, and it is often used in airport runways, railways, highways, houses, tunnels, and other projects in permafrost areas. It is also used in pipeline projects in permafrost areas; along with the TAPS with high ice content, polyurethane materials were used to insulate the pipeline to prevent thawing; the CRCOP was coated with 80 mm of thick polystyrene as an insulation layer to minimize the thermal distribution to the poor engineering geological conditions. In-site monitoring and indoor tests of the CRCOP have shown that pipeline insulation can significantly reduce the development of the melting zone around the pipeline [22, 122]. For Norman Wells Oil Pipeline, wood chips were used to prevent the thaw slump in the slope section with a larger slope and higher ice content [2]; the insulation material could retard the thawing rate and decrease pore water pressure

(4) using cooling techniques such as heat pipe and temperature-controlled ventilation. A heat pipe is a kind of heat exchange device that can effectively reduce the temperature of the permafrost. The application performance of heat pipe technology on roads and railways in permafrost areas proves it can effectively reduce the temperature of frozen ground and ensure the stability of the structure's foundation. Heat pipe technology has also been successfully applied to the TPAS and CRCOP in the prevention of freeze damage. The temperature-controlled ventilation pipe can quickly decrease the temperature in the embankment and roadbed and increase the stability of the permafrost soil below and hence of the engineering structure itself, so it played a good role in the prevention of freezing and thawing disasters on the Qinghai-Tibet Railway [128–132]. Although the temperature-controlled ventilation pipe has not been applied in pipeline engineering, researchers have found through numerical simulation that it also has a beneficial effect on slowing down the melting pipeline foundation soil [21]

(5) comprehensive measures. When a pipeline passes through areas with high temperature and ice content, a single mitigation measure may not be able to eliminate the adverse effects of freezing and thawing on the pipeline, so a combination of multiple

measures is required. For example, the overhead section of the TAPS adopted a combination of overhead and heat pipes, and the buried section adopted thermal insulation and active cooling measures to reduce the impact of the pipeline on the permafrost and avoid greater thermal disturbance to the pipeline foundation soil. The high temperature and ice content section of the CRCOP adopted the combination of insulation and heat pipe, replacement and heat pipe, replacement and insulation, and increased wall thickness to ensure the stability of the pipeline foundation soil. At the same time, researchers have also proposed many compound mitigation measures, such as the centrifuge test carried out by Li et al. [124] that combined sandbags and heat pipes, the heat pipes cooling the soil while the sandbags supporting the pipe. The test results prove that the measure can slow the thawing rate of the pipeline foundation soil. In addition, the study also found that the accumulated water in the trench also affects the foundation soil [133]. So, it is necessary to pay attention to the impact of the accumulated water in the pipe trench on the foundation soil, and if necessary, the drainage of the accumulated water in the pipe trench should be carried out

Therefore, based on the concept of pipe-soil interaction, for pipe freeze-thaw disaster mitigation measures, the main starting point is the pipe and the pipe foundation soil. For the pipeline, improve the performance of the pipe and increase the wall thickness of the pipeline to increase the deformability, and control the temperature of the oil or gas to reduce the thermal impact on the frozen soil. For the pipe foundation soil, measures such as replacing the freezing-thawing insensitive soil and applying heat pipes and ventilation pipes to reduce the uneven deformation of the pipe foundation soil are necessary to achieve the purpose of preventing large differential deformation of the pipeline.

5. Research Prospects

Researchers have conducted a lot of studies on the causes, processes, and mitigation measures of freezing-thawing disasters of buried energy pipelines in the permafrost regions and have obtained rich research results. However, there are still some problems in this field. For example, the analysis of the hydro-thermal-mechanical coupling process of pipeline-soil interaction is relatively simple; when a pipeline passes along a slope, runoff channels form around the pipe, which exacerbates water and heat erosion; the development process and scope definition of the melting circle of the soil around the buried high-temperature pipeline; and whether the deformation mechanisms of the warm crude oil pipeline and the cold natural gas pipeline are the same. Based on the current progress, the research that needs to be carried out in the future mainly includes

(1) improving pipeline monitoring system in permafrost regions. The complete long-term sequence of on-site monitoring data is of great significance for the comprehensive analysis of pipeline freezing-thawing disasters. Therefore, in the future, it is necessary to develop new sensitive, high-precision, corrosion-resistant, freeze-thaw, and erosion-resistant strain sensors that can accurately measure the deformation of the pipeline. At the same time, it is necessary to periodically calibrate the position of the temperature and moisture probe to accurately reflect the ground temperature change of the pipeline foundation soil

(2) monitoring the surface displacement along the pipeline and using advanced ground monitoring technology, such as GIS, In-SAR, remote sensing, and ground penetrating radar, to monitor the ground displacement. Besides, the monitoring technology should be combined with traditional point-line data to focus on the areas prone to freezing and thawing disasters while monitoring the effectiveness of mitigation measures

(3) optimizing the numerical calculation model. A comprehensive hydrothermal three-field coupling numerical model should be established, combined with on-site monitoring data to optimize and change the model and systematically analyze the pipe-soil interaction mechanism, influencing factors, and effectiveness of mitigation measures in permafrost regions

(4) carrying out a large number of indoor model tests and optimizing the model test, including parameters, equipment, and similarity. Through the analysis of the pipe-soil interaction mechanism and the effectiveness of mitigation measures under different freeze-thaw disasters in permafrost regions, the laboratory tests can provide references for the design, construction, and operation of pipelines in permafrost regions

(5) evaluating the effectiveness and adaptability of mitigation measures. A variety of mitigation measures have been adopted in order to reduce the impact of freeze-thaw disasters on the pipeline; a variety of mitigation measures have been adopted. The effectiveness and applicability of these mitigation measures need to be further qualitatively and quantitatively evaluated to provide a certain reference for pipeline construction in permafrost regions. In combination with the mitigation measures of other buildings in the permafrost areas, new measures are developed as a technical reserve for the prevention and control of pipeline freezing-thawing disasters

6. Summary

Climate change, pipe temperature, and freezing-thawing cycles all have an impact on the stability of the foundation soil of buried pipelines in permafrost regions. Differential frost heave and thaw settlement are the two leading causes of pipeline stability problems. Also, some other key influencing factors must be considered, such as slope instability, transitions between permafrost and talik, frost mound, aufeis, and ice scouring. This article reviewed recent progress in research on geotechnical hazards in permafrost regions, such as the impact of thaw settlement, frost heave, slope instability, and other frost hazards along buried pipelines.

For buried pipelines in permafrost regions, the thermal-hydro-mechanical (THM) interactions between the pipeline and the soil are the major causes of the instability of the foundation soils of buried pipelines. Their interactions are required to assess the stress and deformation states of the pipeline. Field observations and monitoring are necessary to study the pipeline-soil interaction in permafrost regions. In the meantime, it can monitor the thermal and mechanical stability of the pipeline systems. Due to climate warming, pipeline-soil interactions will become more complicated, and the stability of the buried pipeline in permafrost terrain may be endangered. Some research has been done on the hydrothermal and mechanical stability of the foundation soils of the buried energy pipelines in permafrost regions from 1973 to 2020. There are still many problems that require further research and discussion. The research on the hydrothermal and mechanical stability of pipeline foundation soil in permafrost regions mainly relies on numerical simulation and experimental research because of the paucity of time series of field monitoring data. Meanwhile, the numerical model simulation only considers the steady-state process of ground freezing and thawing. The freezing-thaw process is not coupled, and the single working condition considered in the indoor model test cannot quantitatively analyze the frost heave and thaw settlement. For oil and gas pipelines in complex permafrost environments, more laboratory tests, numerical simulations, and field test data are needed to understand the impact of freeze-thaw hazards on pipelines and the application of mitigation measures. In permafrost regions, the buried pipeline-soil interactions are complex, coupled processes. To better understand the interactive processes, more accurate models are deemed necessary.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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