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Review Article

Analysis of Necessity and Feasibility for Ground Improvement in Warm and Ice-Rich Permafrost Regions

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Characterized by low bearing capacity and high compressibility, warm and ice-rich frozen soil is a kind of problematic soil, which makes the original frozen ground formed by of that unreliable to meet the stability requirements of engineering infrastructures and foundations in permafrost regions. With the design and construction of major projects along the Qinghai-Tibet Engineering Corridor (QTEC), such as expressway and airport runway, it is a great challenge to favor the stability of overlying structures by formulating the proper engineering design principles and developing the valid engineering supporting techniques. The investigations carried out in recent years indicated that warm and ice-rich permafrost foundations were widespread, climate warming was significant, and the stability of existing engineering structures was poor, along the QTEC. When the warm and ice-rich frozen ground is used as the foundation soil, the implementation of ground improvement is an alternative measure to enhance the bearing capacity of foundation soil and eliminate the settlement of structures during operation, in order to guarantee the long-term stability of the structures. Based on the key factors determining the physicomechanical properties of frozen soil, an innovative idea of stabilizing the warm and ice-rich frozen soil based on chemical stabilization is proposed in this study, and then, an in situ ground improvement technique is introduced. This study intends to explore the feasibility of ground improvement in warm and ice-rich permafrost regions along the QTEC based on in situ chemical stabilization and provide the technical support and scientific reference to prevent and mitigate the hazards in the construction of major projects in the future.

1. Introduction

The Qinghai-Tibet Engineering Corridor (QTEC) runs from Golmud to Lhasa, traversing 550 km of permafrost regions in the interior of the Qinghai-Tibet Plateau (QTP) in north-south direction [1]. Permafrost refers to soil or rock that remains at or below 0°C for at least 2 years [2–4]. Permafrost on the QTP is thin, thermally unstable, and sensitive to climate change [5–7], and the warm and ice-rich frozen soil is widely distributed [8, 9]. The physicomechanical properties of the warm and ice-rich frozen soil feature high unfrozen water content [10], low shear strength [11, 12], and high compressibility [13, 14], leading to the fact that the foundation soil with the warm and ice-rich frozen soil is low in bearing capacity and large in settlement. Now, the existing linear projects, such as the Qinghai-Tibet Highway (QTH), the Qinghai-Tibet Railway (QTR), the Golmud-Lhasa oil product pipeline, and the optical cable from Lanzhou to Lhasa, are all located in the QTEC within a width of less than 10 km [9, 15]. During the operation of the QTH and the QTR, remarkable settlement of the embankments occurred in warm and ice-rich permafrost regions [16, 17], posing an adverse effect on the traffic safety. With the design and construction of major projects along the QTEC, it is urgent to formulate the proper engineering design principles and develop the valid engineering supporting techniques.

In civil engineering, the original foundations with the poor performance in stability, deformation, or permeability generally need to be reinforced to form the artificial foundations [18]. Based on the stabilization mechanism of ground improvement, the mitigation techniques can be divided into as follows: remove and replace, compaction or densification, drainage or consolidation, and reinforcement and modification [19, 20]. Owing to the existence of ground ice, the geotechnical properties of permafrost are affected by the variation of ground temperature when it serves as the foundation materials for construction [21]. At present, the primary technique for ground improvement in warm and ice-rich permafrost regions along the QREC is the cast-in-place piles. With the advancement of engineering machinery, materials, and construction technology, the method of ground improvement tends to be diverse, mechanical, and intelligent [19], which creates many possibilities of technology for ground improvement in permafrost regions. For the demand of economic development and national safety, the proposed major projects, such as expressway [15] and airport runways [22], will be built along the QTEC. More importantly, the workability of foundation soil under static and dynamic loading must satisfy the strict requirements of stability and deformation for high-grade roadways. So, how to guarantee the favorable serviceability of major projects in warm and ice-rich permafrost regions along the QTEC is of vital importance. Therefore, in the context of eco-environmental protection, there is practical significance to develop a suitable technique for ground improvement to enhance the serviceability and durability of major projects in the future.

By reviewing the current situation of frozen ground conditions for engineering geology, climate changes, and existing engineering structural stability along the QTEC, this study explains the necessity of ground improvement in warm and ice-rich permafrost regions affected by climate warming and anthropogenic activities. Then, an innovative idea of stabilizing the warm and ice-rich frozen soil based on chemical stabilization is proposed, according to the excellent performance of soil stabilizer for improving the geotechnical properties of soil. Moreover, an effective soil stabilizer and an in situ technique for ground improvement are introduced. Eventually, in situ tests extending the perspective of composite foundation applied in warm and ice-rich permafrost regions for ground improvement are introduced. As a result, this study provides scientific and reasonable insight into the design and construction of major projects along the QTEC in the future.

2. Analysis of Necessity

2.1. Frozen Ground Conditions for Engineering Geology along the QTEC. A better understanding of the frozen ground conditions for engineering geology along the QTEC provides the scientific guideline for construction site selection, engineering design principle, construction technology, operation maintenance, and freezing-thawing hazard prevention to major projects in permafrost regions [9]. When permafrost serves as a geological body supporting the overlying engineering structures, its mean annual ground temperature (MAGT) and ice content determine the bearing capacity of the foundations.

Combined with the method of fuzzy C-means algorithm and analytic hierarchy process, Chai et al. [23] evaluated the frozen ground conditions for engineering geology along the QTEC based on the visualization of geo-information system. The results indicated that the engineering geology conditions in warm and ice-rich permafrost regions were poor. Similarly, taking the distribution of permafrost, ground temperature, and ice content into consideration, Jin et al. [24] analyzed the frozen ground conditions for engineering geology along the QTH and the QTR and then described the general characteristics of engineering geology based on the three-level regionalization. Both the MAGT and the ice content are principal parameters determining the engineering geology characteristics of frozen ground [25], affecting the selection of foundations of engineering infrastructures and the design principles in permafrost regions [26]. The MAGT is an indicator of thermal regime of permafrost, and it is sensitive to climate changes and engineering activities, representing the stability of permafrost conditions [24]. Based on the MAGT, the thermal regime of permafrost along the QTEC was divided into four types: extreme unstable ($-0.5^{\circ}C < MAGT \leq 0^{\circ}C$), unstable ($-1.0^{\circ}C < MAGT \leq -0.5^{\circ}C$), basically stable ($-2.0^{\circ}C < MAGT \leq -1.0^{\circ}C$), and stable ($MAGT \leq -2.0^{\circ}C$) [8]. This study analyzes the thermal regime of the frozen ground conditions for engineering geology along the QTEC based on the MAGT simulated by GIPL 2.0 permafrost model (Figure 1) [27]. The investigations indicated that the MAGT is above $-1.0^{\circ}C$ and the thermal stability of permafrost is poor in the following regions: Qingshuihe basin, Beiluhe northern basin, Kaixinlin partial hills, Buquhe basin, Wenquan basin, etc.

Meanwhile, ice content, as a determining parameter for the evaluation of frozen ground conditions for engineering geology, controls the thawing settlement properties of frozen soil [28]. Hence, the classification of frozen ground conditions for engineering geology based on the ice content in the frozen soil layer provides the guideline for engineering design and freezing-thawing hazard prevention [24]. Based on the volumetric ice content, permafrost can be divided into five categories: ice-poor ($i_v \leq 10\%$), icy ($10\% < i_v \leq 20\%$), ice-rich ($20\% < i_v \leq 30\%$), ice-saturated ($30\% < i_v \leq 50\%$), and ice layer with soil ($i_v > 50\%$) [29]. This study illustrates the distribution of permafrost types along the QTEC (Figure 2) [30]. The data of ice content in the study are from geological investigations for the construction of ±400 kV direct current power transmission line. From Figure 2, the distribution of ice-rich frozen soil is mainly located in the following regions: Kunlunshan mountains, Qingshuihe basin, Kekexili hills and mountains, Beiluhe basin, Fenghuoshan mountains, Kaixinlin mountains, and Tanggula mountains.

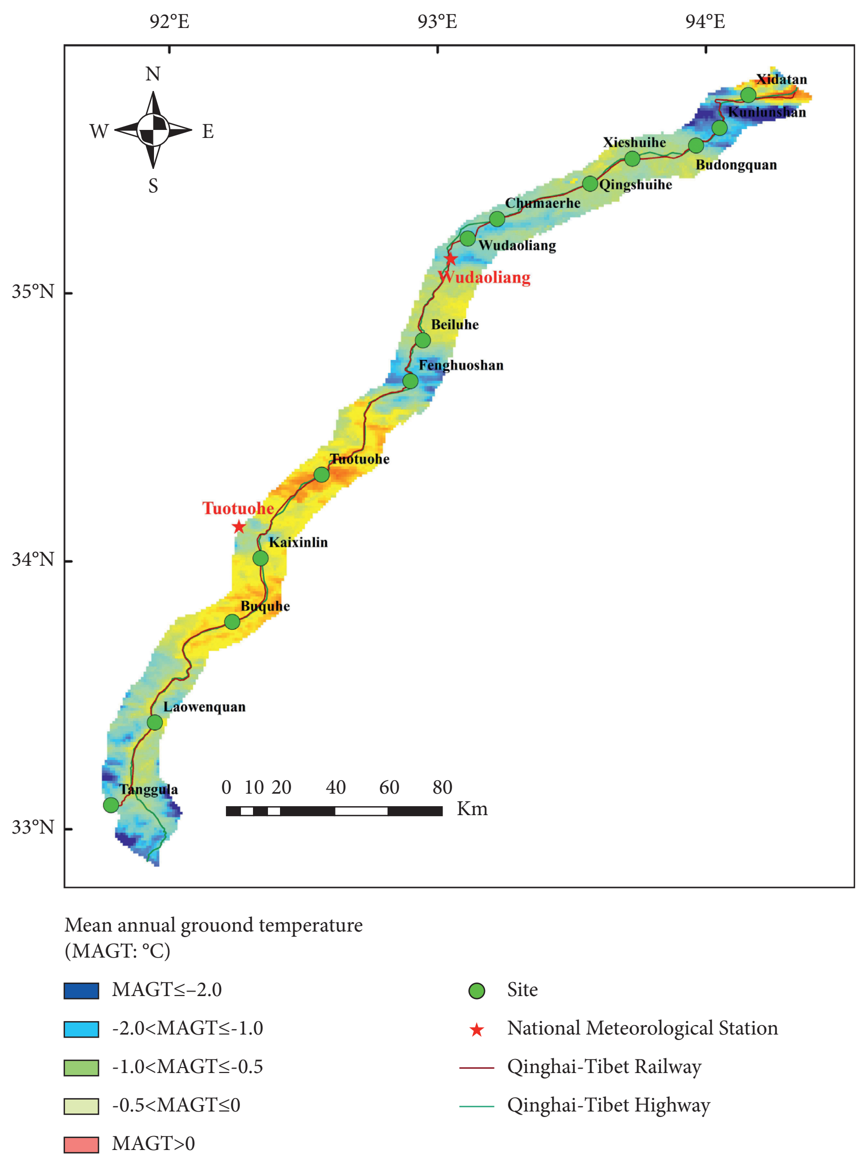

Figure 1: Mean annual ground temperature of permafrost along the QTEC. Note: the ground temperature distribution map was modified based on the data provided by Yin and Niu, and the original data can be used in public for scientific research and downloaded by registration (DOI: https://doi.org/10.11888/Geocry.tpdc.270044).

The evaluation of frozen ground conditions for engineering geology shows that the higher the MAGT, the lower the thermal stability, and the higher the ice content, the higher the thawing settlement risk. Combined with Figures 1 and 2, it can be concluded that the distribution of warm and ice-rich permafrost foundations is widespread and the performance of frozen ground conditions for engineering geology is poor along the QTEC, leading to the higher requirement of countermeasures for the stability of engineering infrastructures and foundations.

2.2. Climate Changing Trends along the QTEC. Permafrost is an interactive product between the ground and the atmosphere [31, 32], and it is sensitive to climate changes [33]. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change presumes that the higher probability of global warming reaches 1.5°C between 2030 and 2052 if the current rate of warming continues [34]. Permafrost on the QTP is a sensitive indicator to global climate change, and its warming is prior to the surrounding regions; it is also a reactive amplifier of global climate change, and its temperature increases faster than the global average [35, 36]. Climate change is one of the significant parameters in permafrost engineering, and it determines the long-term performance of engineering structures. Therefore, when selecting the design principles, taking the effect of climate change on permafrost engineering into consideration is of vital importance [37]. The following contents will analyze the changing trends in climate along the QTEC based on the mean annual air temperature (MAAT) (Figure 3) and the mean annual surface temperature (MAST) (Figure 4) obtained from two national meteorological stations (Wudaoliang and Tuotuohe). From Figure 3, the

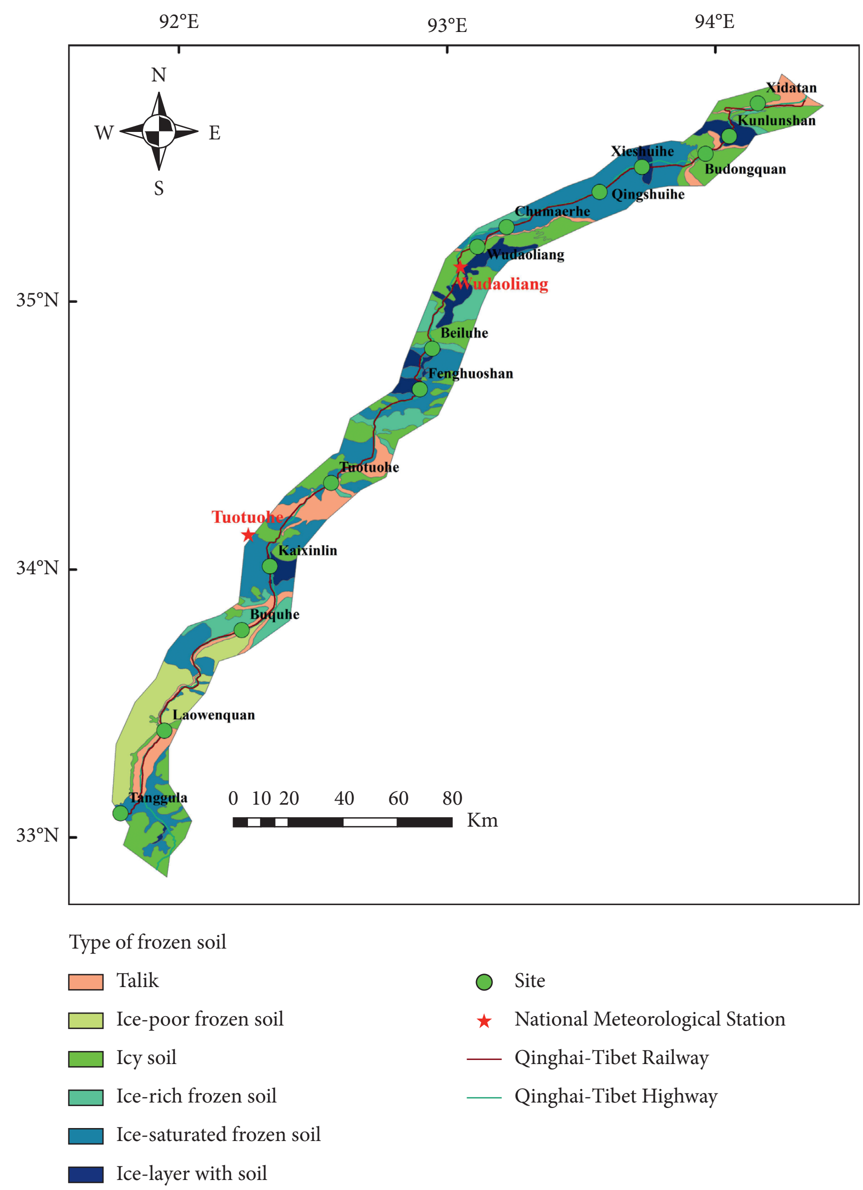

Figure 2: Types of frozen soil along the QTEC (source: reproduced with permission from Chai 2018, a coauthor of this study. Copyright 2018 Journal of Cold Regions Engineering).

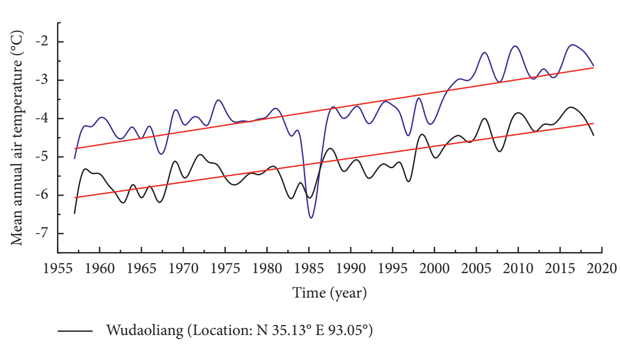

Figure 3: Variations of mean annual air temperature at national meteorological station within the QTEC from 1957 to 2019.

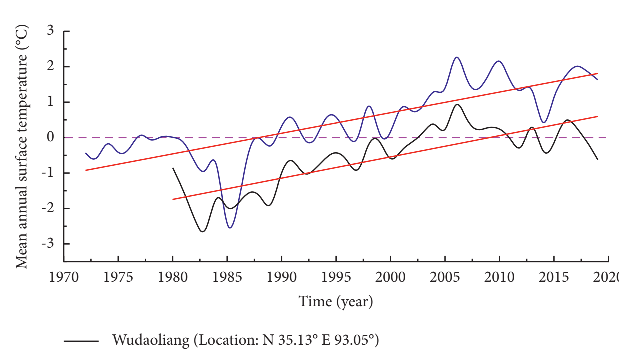

Figure 4: Variations of mean annual surface temperature at national meteorological station within the QTEC from 1972 to 2019.

MAAT rose by 2.04°C from −6.48°C in 1957 to −4.44°C in 2019 at Wudaoliang Station, and it rose by 2.42°C from −5.05°C in 1957 to −2.63°C in 2019 at Tuotuohe Station. Similarly, from Figure 4, the MAST rose by 0.24°C from −0.85°C in 1980 to −0.61°C in 2019 at Wudaoliang Station, and it rose by 2.07°C from −0.43°C in 1972 to 1.64°C in 2019 at Tuotuohe Station. Combined with Figures 3 and 4, it can be concluded that climate warming is obvious and the surface temperature increases significantly within the QTEC. Under climate warming scenarios, permafrost degradation along the QTEC is characterized by increasing ground temperature, thickening active layer, and melting ground ice [1, 38]. Thawing of permafrost generally results in the ground surface subsidence, which causes the failure of the overlying engineering structures and threatens their safety operations [39]. Hence, it is of great scientific significance to take the effect of climate change on permafrost engineering into consideration.

2.3. Thermomechanical Stability of Existing Linear Projects. Clarifying the interaction between permafrost and foundations of existing engineering infrastructures facilitates the adaptive analysis of countermeasures towards the application of high-grade roadways and lays a solid base for the selection of supporting techniques and for the formulation of design principles towards major projects in the future.

Engineering activities in permafrost regions inevitably disturb the energy balance on the ground surface, which affects the thermal regime of the underlying permafrost [3], leading to permafrost warming, permafrost table descending, and ground ice melting [40, 41]. In 1954, the operation of QTH was initiated with gravel pavement, and then, it was completely capped with asphalt pavement in 1985 [40]. The monitoring results indicated that permafrost degradation was significant and thawed settlement of embankments was serious along the QTH [5, 42]. Though some countermeasures, such as elevating embankment height, constructing thermal insulation berm, and placing insulation materials in the embankment, were used to reinforce the embankments based on the principle of permafrost protection or thawing rate control, some damages to the embankments occurred subsequently [43]. At present, the subgrade distress mainly results from differential settlement [16, 42], and the pavement damages are characterized by transverse cracking, potholes, and longitudinal cracking [30]. Until now, pavement damages along the QTH have not been entirely solved, and large-scale rehabilitations and remedies still need to be carried out every 2-3 years [44, 45].

The construction of the QTR adopted the advanced design idea, "cooled roadbed," and numerous cooling measures by adjusting solar radiation, and heat convection and conduction with modification of configurations were employed to cool the permafrost beneath the embankments [36]. The investigations indicated that the permafrost table beneath the crushed rock embankment in warm permafrost regions was uplifted, but the ground temperature in deep depth experienced a warming trend [46]. Meanwhile, some failures of the measures, including clogged crushed rock layer [47] and damaged thermosyphon [48], pose a challenge to these active cooling measures. During the operation of the QTR, the embankment deformations were mainly due to thawing settlement [17], and the differential settlement was obvious in the embankment-bridge transition section [49]. For operation maintenance, the railway administrative bureau carried out supplementary ballast for track line regularity. In a word, the thermomechanical stability of the existing linear projects mentioned above along the QTEC was poor in some sections. Therefore, it can be concluded that the existing supporting techniques and the mitigation countermeasures are incapable to serve the construction of high-grade roadways because of its higher requirements for structural stabilization and its extensive disturbance to the thermal regime of the underlying permafrost [50].

Hence, faced with the poor frozen ground conditions for engineering geology and the current situation of climate warming, it is imperative to transform our insight into ground improvement as adopted in problematic soils to deal with the severe challenge in the construction of major projects in warm and ice-rich permafrost regions, and develop reliable countermeasures to guarantee the stability of foundations in permafrost engineering.

3. Analysis of Feasibility

3.1. Idea of Chemical Stabilization of Warm and Ice-Rich Frozen Soil. Soil stabilization is the collective terminology for any physical, or mechanical, or chemical, or any combination of such methods, employed to improve the geotechnical properties and performance of problematic soil to make it meet the requirements of engineering construction [51, 52]. Chemical stabilization involves the mixing of base soil with one of or a combination of soil stabilizers of powder, slurry, or liquid to improve the geotechnical properties such as permeability, shear strength, bearing capacity, and workability [52]. As a result, a series of reactions may occur in chemically stabilized soil system, including hydration, ion exchange, cementation, flocculation, and carbonation. The soil stabilizer refers to an available material that reacts physicochemically among base soil, water, and air, to improve the geotechnical properties of base soil [53]. Soil stabilizer acts on the soil to reduce the affinity of clay particles to water and thin the thickness of bound water film [54, 55], which creates a potential for reducing free water content and enhancing physicomechanical properties of the warm and ice-rich frozen soil. Moreover, soil stabilizer can alter the soil microstructure to reduce the compressibility of soil skeleton [56, 57] and thus may decrease the thawing settlement of the warm and ice-rich frozen soil. The category of soil stabilizer can be divided into inorganic soil stabilizer, ionic soil stabilizer, organic soil stabilizer, and bioenzyme soil stabilizer based on their stabilizing mechanisms [58, 59]. Before commencing the warm and ice-rich frozen soil stabilization, it is beneficial to review the stabilization mechanisms of soil stabilizer and its effects on soil improvement.

Inorganic soil stabilizers are generally dry powder, mainly including cement, lime, fly ash, and industrial slag;

these soil stabilizers react with base soil to generate the cementitious products, such as calcium silicate hydrate [60, 61], calcium sulfate hydrate, and calcium aluminate hydrate [62, 63]. These cementitious products can bond soil particles to form stable soil skeleton and fill the voids in soil to enhance densification and strength [64, 65]. Chai et al. [66, 67] performed a series of laboratory tests to improve the warm and ice-rich frozen soil with Portland cement and various additives, and the results indicated that the selected optimum additives are favorable to enhance the geotechnical properties of the stabilized soil.

Ionic soil stabilizer depends on the process of ion-exchange reactions to deprive soil particles of its water affinity and thin the thickness of bound water film and thus decrease the plasticity index of soil [68, 69]. Meanwhile, subjected to ionic soil stabilizer, the volume and diameter of pore in the stabilized soil decrease, reducing the compressibility of soil [70, 71]. Zhang et al. [72, 73] adopted the Toogood and Roadbond, respectively, to stabilize the warm and ice-rich frozen soil, and the results showed that the shear strength is increased and the compressibility is decreased for the stabilized soil.

Organic soil stabilizer refers to synthetic polymer solutions or emulsions, such as sulfonated oil, sodium silicate, epoxy resin, and polyacrylamide [52, 58]. Based on polymerization reactions, this kind of soil stabilizer forms organic macromolecular chains between voids to aggregate soil particles [74, 75], thus enhancing the strength and durability of the stabilized soil [76, 77]. However, there is no literature report about stabilizing frozen soil with organic soil stabilizer.

Bioenzyme soil stabilizer, as a kind of catalyst without becoming the end product, is fermented from vegetable extracts [58, 64, 78]. Bioenzymes catalyze the microorganism reactions between organic matters in soil particles and accelerate the cation-exchange process to reduce the electrical double-layer thickness [68, 79]; thus, the geotechnical properties of the stabilized soil with bioenzyme are significantly improved. However, the disadvantages of bioenzyme are characterized by biodegradation and sensitivity to the variation of temperature and pH [80]. In addition, the strength of the stabilized soil with bioenzyme is obviously decreased when the stabilized soil is soaked in water [58, 81]. Considering the successful application of various soil stabilizers in improving the geotechnical properties of problematic soil, there is theoretical and practical feasibility of the stabilization of the warm and ice-rich frozen soil. The key factors determining the physicomechanical properties of frozen soil include soil, water, temperature, salinity, and load [3]. Therefore, the viable alternative to improve the geotechnical properties of the warm and ice-rich frozen soil based on chemical stabilization is summarized in Figure 5.

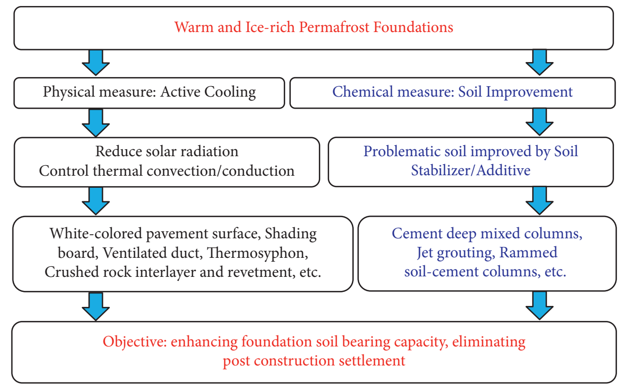

Figure 5: Category of frozen soil improvement.

3.2. Selection of Valid Stabilizer for Stabilizing Warm and Ice-Rich Frozen Soil. After reviewing the stabilizing mechanisms mentioned above, it is concluded that soil stabilizers, other than bioenzyme, can be theoretically used to improve the warm and ice-rich frozen soil. Since the ionic and organic stabilizers are liquid chemicals, they may increase the total water content in frozen soil, thus possibly causing the increase in unfrozen water and poor performance in engineering properties. Therefore, based on the unacceptable supplementary of total water content in soil stabilization, the optimum inorganic soil stabilizer of dry powder, which can react with the warm and ice-rich frozen soil at negative temperature, is emphatically selected.

According to the available materials studied, the sulphoaluminate cement, mainly composed of anhydrous calcium sulphoaluminate, dicalcium silicate, and gypsum [82], is characterized by fast hardening [83, 84] and hydration at negative temperature [85, 86]. Subsequently, our team colleagues conducted a series of laboratory tests to stabilize the warm and ice-rich frozen soil with sulphoaluminate cement. The comprehensive experimental aspects on chemical stabilization of the warm and ice-rich frozen soil are covered, and the results are as follows.

Sun et al. [87] conducted the laboratory tests, including mercury intrusion porosimetry, scanning electron microscopy, unconfined compressive strength, time-domain reflectometry, X-ray diffraction, and thawing compression tests, and found that the cementitious hydration products occur within the stabilized soil and fill the pore volume. Then, they established the correlation between microstructural characteristics and mechanical properties of the stabilized soil. One important point of the above tests mentioned is to determine the relationship between compressibility and pore orientation fractal dimension. Additionally, Yin et al. [88] performed centrifuge and freeze-dryer tests to explore the law of water transformation among free water, mineral water, and bound water during the process of soil stabilization and explained its effect on the strength of the stabilized soil. Through laboratory studies, the performance of sulphoaluminate cement-stabilized soil indicated that there is a decrease in free water, pore volume, and compressibility and an increase in unconfined compressive strength [87–90]. More importantly, it was found that the clubbed shape of ettringite occurs and establishes a skeleton structure in the pore volume of the stabilized soil, while the hydration products, such as aluminum hydroxide gel and calcium silicate hydrate gel, agglomerate and cement the soil particles, resulting in a remarkable decrease in soil particles between 0.002 mm and 0.075 mm [90].

In conclusion, sulphoaluminate cement can be used to improve the physicomechanical properties of the warm and ice-rich frozen soil and enhance its geotechnical properties; thus, it is a valid stabilizer for chemical stabilization. More importantly, compared with the currently used measure of active cooling, the physicomechanical properties of the stabilized soil are no longer affected by temperature variations, so the long-term stability and durability of geotechnical properties of the stabilized soil can be guaranteed in the context of climate warming.

3.3. Technology for Ground Improvement in Warm and Ice-Rich Permafrost Regions. Similar to soft soil, the physicomechanical properties of the warm and ice-rich frozen soil are characterized by high compressibility [91, 92], and its compression process is a combination of consolidation and creep [93], leading to an unreliability of foundations in frozen ground to meet the stability requirements of engineering infrastructures in permafrost regions. Based on the laboratory investigations, it is concluded that the warm and ice-rich frozen soil can be stabilized by soil stabilizers. Also, ground improvement by dry deep mixing refers to a reinforcement method mixing soil stabilizer and base soil in situ, which creates the applicability of dry jet mixing pile used in warm and ice-rich permafrost regions.

A dry jet mixing pile refers to a stabilized soil column element bearing vertical load; they can be installed with the assistance of special rotatory tool, such as a machine with several shafts equipped with mixing blades and several nozzles for pumping dry powder stabilizer using compressed air, during which a series of physicochemical reactions occur within the mixture of in situ base soil and the pumped soil stabilizer [94, 95]. Figure 6 illustrates the installation steps: positioning, drilling, elevating, and pile forming [19, 94].

The dry jet mixing pile is a kind of adhesive column with higher strength and stiffness compared with interpile soil and consists of a composite foundation with interpile soil to undertake the overlying structural load [96]. The shear strength of interpile soil is increased after installation, thus enhancing composite foundation soil bearing capacity [97, 98] and eliminating postconstruction settlement [99, 100]. More importantly, compared with currently used cast-in-place bored piles, the installation of dry jet mixing piles fully exploits the base soil properties in situ and makes no transfer of the base soil elsewhere, thus reducing the transportation cost and construction investment. Also, the advantages of dry jet mixing pile, as an environment-friendly geotechnology, are flexible installation, low noise, and small vibration [95, 97]. Through the above discussions and reviews, it is clear that the proposed ground improvement method by dry deep mixing is feasible to adjust the stress conditions of original foundation soils in warm and ice-rich permafrost regions. Therefore, adopting the composite foundation of dry jet mixing pile for supporting the stability of major projects within the QTEC is tentative and practical.

3.4. In Situ Test of Ground Improvement in Warm and Ice-Rich Permafrost Regions. To practice the idea of chemical stabilization of the warm and ice-rich frozen soil in permafrost regions, our team colleagues conducted some in situ tests at Beiluhe on the QTP, in August 2017 (Figure 7). In the experiment, the dry jet mixing pile was installed without strict accordance with the technical steps illustrated in Figure 6. The process was implemented by an excavator; the excavated frozen soil and dry stabilizer were subsequently mixed, backfilled, and compacted. The thermistors were located at different depths of the backfilled mixture to measure hydration heat during the curing period. The details of installation can be seen in the paper by Chai et al. [101]. Meanwhile, to verify the effectiveness of ground improvement, the pressuremeter test was performed after 70 days of curing. Since the dry jet mixing pile serves as a column element bearing vertical load, much attention is concentrated on pile-to-soil stress ratio and load transfer mechanism of pile under static loading in engineering application [102, 103], leading to the fact that the pressuremeter test conducted in situ has no value for reference. However, this in situ experiment is still a meaningful attempt to reinforce foundation soils by chemical stabilization in warm and ice-rich permafrost regions, and it can provide a reference for the selection and formulation of supporting technology towards major projects in the future.

4. Research Work for Future

The essence of frozen soil is different from thawed soil due to the presence of ice [104, 105], leading to the fact that ice is the most important constituent controlling the strength and deformation of frozen soil [104, 106]. When engineering infrastructures and foundations are over or within frozen ground, its stability is affected by thermomechanical properties of frozen soil [107]. Currently, the dominant principle of engineering designs and remedial countermeasures mainly depends on active cooling to prevent frozen soil from thawing and warming. Nonetheless, affected by climate warming and subsequent ground temperature rising, the thermomechanical stability of existing linear projects in warm and ice-rich permafrost regions along the QTEC was poor, meaning that the countermeasures for mitigating hazard are insufficient to acquire the targeted requirements. With the design and construction of major projects along the QTEC, such as expressway and airport runway, it is imperative to reevaluate the effect of climate warming and anthropogenic activities on engineering infrastructures and foundations. Moreover, both the reliable engineering designs and the effective mitigation countermeasure need to be formulated urgently.

Soil stabilization used to improve the geotechnical properties of soil is usually applied in ground improvement. This study proposes an innovative idea of chemical stabilization of the warm and ice-rich frozen soil and introduces a method of in situ ground improvement by dry jet mixing. Although our team colleagues conducted a series of laboratory tests to stabilize the warm and ice-rich frozen soil with sulphoaluminate cement and Portland cement combined

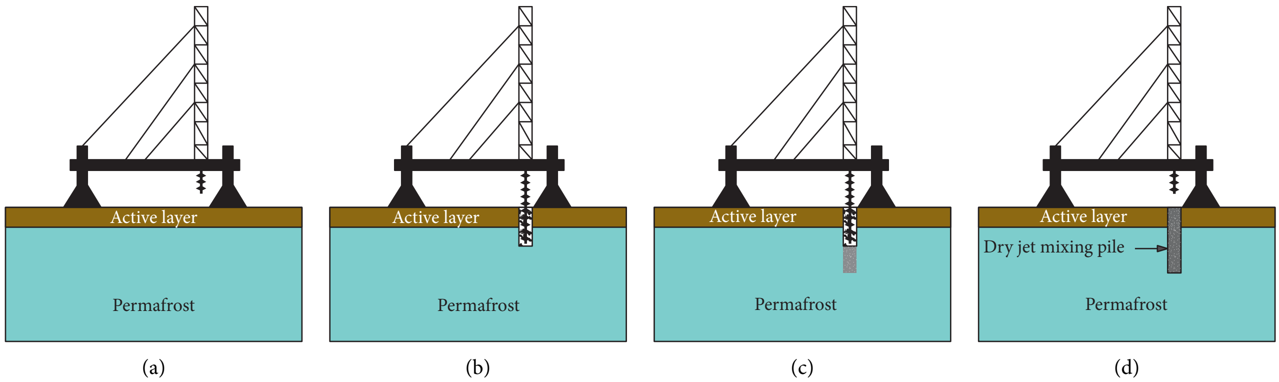

Figure 6: Installation of dry jet mixing pile. (a) Positioning. (b) Drilling. (c) Elevating. (d) Pile forming.

Figure 7: In situ test. (a) Construction site. (b) Pro-improved frozen soil. (c) Postimproved frozen soil.

with various additives, it should be noted that the degree of hydration between frozen soil and soil stabilizer is low, and the strength of the stabilized soil increased slowly at negative temperature. Hence, it is of vital significance to develop high-performance cement with high hydration degree at negative temperature and some highly effective additives used as a stimulator for improving physicomechanical properties of the warm and ice-rich frozen soil. Additionally, the engineering disturbance to original foundation soils caused by the installation of dry jet mixing pile is inevitable, so how to quantify the strength variation between the decrease by installation and the increase by soil stabilization is still a key point in future research. Limited by the field conditions and cost budgets, the installation process of dry jet mixing pile is simplified, leading to producing an unsatisfactory case for the practical use towards future major projects along the QTEC. A further study is the installation of dry jet mixing pile based on practical construction similar to that applied in soft soil regions, and a series of tests, such as static loading test of pile, standard penetration, and core sample survey, should be performed in the field.

5. Summary

(1) The distribution of warm and ice-rich permafrost foundations along the QTEC is widespread. Affected by both climate warming and anthropogenic activities, the thermal regime of permafrost distresses annually and the risk level of thawing settlement increases gradually. The thermomechanical stability of existing linear projects in warm and ice-rich permafrost regions, such as the QTR and the QTH, tends to be poor, indicating that the existing countermeasures for mitigating hazard in permafrost engineering are incapable to be applied directly to major projects in the future.

(2) The key factors determining the physicomechanical properties of frozen soil include soil, water, temperature, salinity, and load. The idea that the geotechnical properties of the warm and ice-rich frozen soil can be improved based on chemical stabilization is feasible. In addition, the method of in situ ground improvement by dry jet mixing is tentative and

practical in permafrost engineering along the QTEC. Before the application of dry jet mixing to major projects in permafrost regions, a series of in situ tests based on technical code for ground improvement still need to be performed.

(3) With the design and construction of major projects along the QTEC, such as expressway and airport runway, principal considerations must be observed as follows: (1) focusing on implementing the zonation of frozen ground conditions for engineering geology along the QTEC; (2) emphasizing on considering the effect of climate warming on engineering infrastructures and foundations in permafrost regions; (3) paying attention to the thermal effect of engineering structures on the underlying permafrost; and (4) adopting proper engineering design principles and developing effective mitigation countermeasures.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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