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Research Article

Field Investigation on Thermal Regime of Permafrost and Talik in a River Terrace, the Interior of Qinghai-Tibet Plateau

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To carry out engineering construction in a permafrost area, it is of great importance to grasp the spatial distribution of permafrost and its hydrothermal characteristics within the scope of engineering activities. Compared with the continuous permafrost area, the permafrost distribution in discontinuous permafrost area is complicated due to existence of island talik, which causes highly poor continuity and uniformity of ground hydrothermal conditions and brings great difficulty and uncertainty to the engineering geological investigation. In the present study, the spatial distribution of permafrost and the freeze-thaw process of shallow ground at the I-stage terrace of a river on the Qinghai-Tibet Plateau were studied based on field investigation including drilling, electrical resistivity tomography, and borehole temperature measurement. The results show that the relict permafrost, patchy permafrost, and island talik are distributed in the limited range of the study area. Among them, the buried depth of relict permafrost layer is in the range of 7 ~ 14 m, while the patchy permafrost layer is in the range of 3.0 ~ 17.0 m depth, and the mean annual ground temperature of both is close to -0.1°C, which belongs to extremely high-temperature permafrost. The seasonal freezing/thawing depths of shallow ground within the relict permafrost, patchy permafrost, and island talik range from 2.5 to 3.0 m. The freezing period of the seasonal freezing layer is 5.5 months, while the thawing period of the seasonal thawing layer is 6 months. The complex plane and spatial distribution of permafrost in the field are closely related to local factors such as topography, geomorphology, groundwater, and lithology of shallow ground. It is believed that the formation of the island talik in the study area is controlled by solar radiation and precipitation infiltration.

1. Introduction

Geotechnical investigation is the basis of engineering design, construction, and maintenance, and its primary task is to identify the engineering geological conditions and hydrogeological conditions in the project area, grasp the spatial distribution of stratum and groundwater, and provide the required geotechnical engineering properties and indexes for engineering design and decision-making. As a special geotechnical body, the engineering properties of permafrost are generally complex and variable. In addition to the lithology of the stratum, temperature and water (ice) content have significant effects on its physical and mechanical properties including density, strength, modulus, and permeability [1, 2]. For conventional thawed soils in temperate regions, their physical and mechanical properties and engineering characteristics remain basically stable under the determination of physical parameters such as lithology, density, and water content. This is not the case for permafrost, which undergoes significant seasonal changes in its hydrothermal conditions along with the energy and mass exchange processes between the ground and atmosphere. The changes in hydrothermal conditions would furtherly result in significant changes in its engineering properties and a series of undesirable geological processes such as frost heave and thaw settlement, which in turn affect the long-term stability of foundations and the safety of infrastructures built upon [3]. Therefore, compared with temperate regions, the engineering geological investigation task carried out in the permafrost area is more complicated and difficult, and it is necessary to find out the spatial distribution of permafrost and grasp the seasonal changes in the hydrothermal condition of the foundation soil. In addition, from the perspective of long-term operation and maintenance of the project, the engineering geological investigation of permafrost also needs to predict the spatial variations in permafrost distribution and the long-term evolution of their hydrothermal conditions under the climate change and engineering disturbances, so as to provide a basis for the adoption of engineering countermeasures [4].

The Qinghai-Tibet Plateau (QTP) is the primary high-altitude permafrost region in the world, with a permafrost distribution area as much as 1.5×10^6 km^2 [5–7]. The distribution of permafrost on the QTP has obvious vertical zonation, but this zonation pattern is often broken by some regional factors including geological tectonism and neotectonics, as well as the geothermal and water systems; in addition, lithology, topography, vegetation, and local climate factors can have significant effects on the spatial distribution of permafrost [8, 9]. Therefore, the overall spatial distribution of permafrost on the QTP is poorly continuous, with extremely heterogeneous thickness and temperature distribution. Within different permafrost areas, various types of taliks can occur; based on the causes of their generation and the factors that determine their existence, they can be classified as tectonic-geothermal taliks, surface water (rivers, seasonal running water, lakes, ponds, etc.) taliks, and infiltration-radiation taliks [10, 11]. A large talik is the preferred place for engineering construction in permafrost areas; however, in case of island taliks, discontinuities and significant differences in hydrothermal conditions of foundation soils within the local area can lead to differential deformation of engineering structures and related damages [12]. Therefore, how to conduct a sound engineering geological investigation in the isolated talik is the primary challenge in front of engineering designers and researchers.

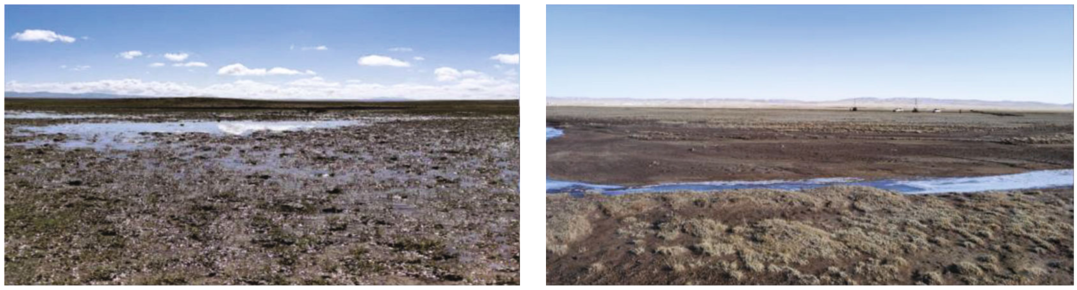
The means of engineering geological investigation in permafrost area include borehole drilling, pit shaft, and trench prospecting, as well as integrated geophysical prospecting techniques such as electrical, seismic, gravity, radiometric, ground-penetrating radar, geomagnetic, and neutron logging. In terms of conventional method, drilling and pitting are more commonly used and are necessary and direct means of permafrost geological investigation. The main purpose of drilling is to determine the presence of permafrost, the upper and lower limits of depths of permafrost layer, the ground temperature, the ice content conditions, and the lithology. The main purpose of pit prospecting is to obtain the thickness of the active layer and the basic properties of the soil within the active layer. In China, the application of geophysical prospecting technology in permafrost investigation began in the 1950s, and systematic research work began in the early 1960s. Geophysical prospecting has many advantages such as fast, low cost, flexible and variable profile layout, various survey means, and continuous profile data. It has significant advantages in delineating the distribution range of permafrost and taliks, detecting the thickness of ground ice and frozen loose sediments, etc., and has played an active and important role in permafrost-related mapping work [13]. At present, the widely used and promising geophysical prospecting techniques in permafrost investigation and related research work are high-density resistivity tomography and ground-penetrating radar, in addition to the geophysical logging and transient electromagnetic methods that have been applied in recent years [14–18]. However, engineering geological investigation methods are constantly updated and developed. From the perspective of engineering construction and long-term operation and maintenance, for different engineering sites and engineering structures, how to reasonably select the corresponding investigate techniques and methods, and on this basis, how to scientifically determine the number of boreholes, geophysical profiles, and their spatial locations currently are still having certain difficulties in actual engineering practice.

Aiming at the island talik field on the I-stage terrace of a river in the QTP, the spatial distribution and hydrothermal conditions of the talik and the permafrost in the site were investigated using methods including drilling, borehole temperature measurement, and high-density resistivity tomography. Through comprehensive investigation, the spatial distribution of permafrost and island talik in the field, as well as the upper limit, lower limit, thickness, temperature, and other characteristic parameters of the permafrost, have been preliminarily identified. On this basis, combined with the development mechanism of the taliks in the permafrost area and the existing research results in the study area, an in-depth analysis of the origin of the island talik in the field was carried out. Finally, based on the engineering geological survey tasks, the current relevant specification requirements, common survey methods, engineering design, and operation and maintenance requirements are discussed, and the existing problems and future research directions are expounded. It is hoped that the present study can provide references for the future engineering geological investigation work in a discontinuous permafrost area.

2. Study Area and Methods

2.1. Study Area. The study area is located in the hinterland of the QTP, an I-stage terrace on the right bank of a certain river, with an altitude of 4526-4532 m, and the area is sparsely populated with a harsh natural environment. The site is wide and flat with local undulations and slopes are $<5^\circ$, and mounds, swamps, streams, and shoals are distributed intermittently. The vegetation cover is generally between 10 and approximately 40%, but the distribution is not uniform; the lower part of the terrain is alpine meadow with higher coverage, while the higher part of the terrain is alpine grassland with lower coverage.

The maximum thickness of quaternary sediments on the ground surface is 5 m, including surface clay, aeolian sand, silty clay, glutenite alluvium and diluvium layer, and lacustrine formation layer with gravel and silty clay, and the bedrock is a stratum constructed from compound sand,



(a) (b)

FIGURE 1: Site topography at the study area in summer (a) and winter (b).

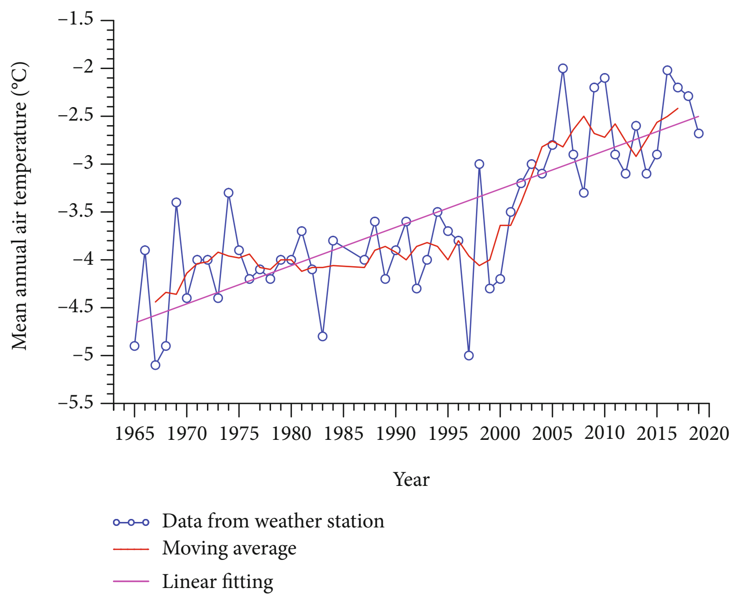


FIGURE 2: Mean annual air temperature in the study area from 1965 to 2019.

gravel, and mudstone deposited in the river and lake. There is a seasonal river developed across the study site from south to north, forming large ponds, shoals, and swampy wetlands in summer and autumn in the relatively low-lying areas, and freezing in winter to form a break in the flow. The higher part of the study site is relatively dry (Figure 1).

2.2. Climate Warming and Humidification Processes in the Study Area. To analyze the climate changes in the study area, data of mean annual air temperature (MAAT) and annual precipitation (AP) from 1965 to 2019 from a national meteorological station near the study area were collected, as shown in Figures. 2 and 3. The data showed that, in the past 50 year, climate warming and humidification processes in the study area were very obvious, which coincides with the climate changes on the whole Qinghai-Tibet Plateau.

In terms of MAAT, its multiyear average increased by around 2°C from 1965 to 2019. During the period, the variations in MAAT can be roughly divided into three stages, among which the increases in the two decades from 1965 to 1975 and 1998 to 2008 were significant, while, in the period from 1975 to 1998, the MAAT remained relatively stable. In terms of AP, it fluctuated between 150 and 500 mm over the past 50 years, showing a slow increasing trend in general and a fluctuating upward trend in terms of moving average. Since 2000, the AP has fluctuated around 350 mm.

The process of persistent warming and humidification of the plateau climate has a close relationship with the degradation of permafrost, the development of taliks, the increase of surface runoff, and the change of groundwater level on the plateau. The changing laws and processes of environmental meteorological conditions on a regional scale are very important for permafrost engineering geological investigation and are important environmental boundaries affecting the long-term hydrothermal conditions of the foundation in the operation and maintenance phase of the project. In the existing engineering practice, it is often necessary to combine global climate change scenarios and engineering service life to make assumptions on the environmental meteorological conditions in the region. For example, a commonly adopted assumption

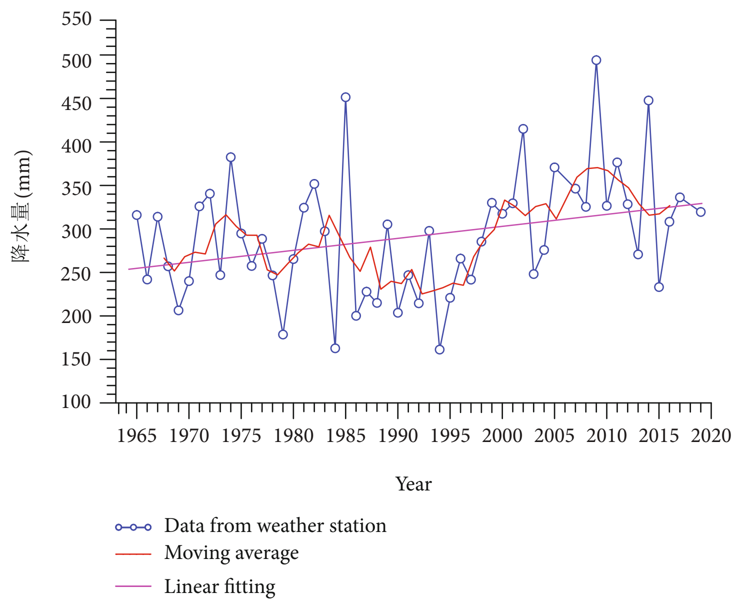


Figure 3: Annual precipitation in the study area from 1965 to 2019.

is that, in the next 50 years, the increase in MAAT in the permafrost region of the QTP is 2.6°C.

2.3. Study Methods. To carry out geotechnical investigation in the study area, methods including field survey, borehole drilling, trench prospecting, geophysical prospecting, ground temperature measurement, and indoor testing were used. In this paper, we focused on combining drill prospecting, borehole temperature measurement, and electrical resistivity tomography (ERT). The borehole temperature measurement used a high-precision thermistor developed by the State Key Laboratory of Permafrost Engineering, Chinese Academy of Sciences. The thermistor has a temperature range of -40~40°C and a temperature resolution of 0.01~0.005°C under negative temperature conditions and 0.01~0.03°C under positive temperature conditions. The ground temperature data were collected automatically by a data acquisition instrument (CR3000, Campbell Scientific) at a frequency of 4 hours/time, and the instrument was powered by a combined solar and battery power supply.

The ERT were performed with the SuperSting R8/IP instrument (Advanced Geosciences, Inc.), which has a distributed cable structure with switches distributed on each electrode for high interference immunity. The data acquisition has 8 channels, and up to 8 sets of data can be measured simultaneously at one time, speeding up the long profile data acquisition and 3D data acquisition. The instrument supply current ranges from 1 mA to 2 A, and the observed potential difference ranges from less than 1 millivolt to several volts. The resolution of the high-density resistivity method detection results is closely related to the electrode distance. In the permafrost area for active layer thickness detection, the general electrode distance is in the range of 0.5-3.0 m, while for detecting permafrost thickness, the electrode distance can be set to 5-10 m. The survey line is generally determined according to the depth of the target body, and usually the maximum survey line length of a single measurement is more than 5 times the maximum depth to be detected. When the total survey line length is greater than the single time survey line length, the rolling measurement method is used with a rolling length of a quarter of the line length. In this study, the Wenner-Schlumberger compound arrangement was used for detection, the electrode distance was set at 5 m, the survey line length was 400 m, and the total survey line length was 800 m, so the rolling measurement method was used.

3. Results and Analysis

3.1. Boundary between Permafrost and Talik. To identify the spatial distribution of permafrost and talik in the study area, an ERT profile with a total length of 800 m was carried out in the study area in an east-west direction, passing through four boreholes with ground temperature measurement, 8#, 9#, 10#, and 11# from east to west, respectively. The results of the ERT are shown in Figure 4. The overall resistivity distribution within the survey line is very heterogeneous, reflecting the complexity of permafrost distribution in the study area. From east to west, based on the resistivity distribution, the 800-meter range of the survey line can be roughly divided into four intervals with high, significantly high, significantly low, and low resistivity values, respectively. Among them, an island-shaped area with significantly high resistivity exists near the 9# borehole, and the width along the survey line is about 80 m. Starting from the borehole 10#, the resistivity of the western section of the survey line is significantly lower than that of the eastern section, and to the westernmost section of the survey line, the resistivity of the shallow strata is relatively high.

To accurately grasp the permafrost distribution along this survey line, the ground temperature profiles of the four boreholes on the survey line on July 5, 2021 are given in

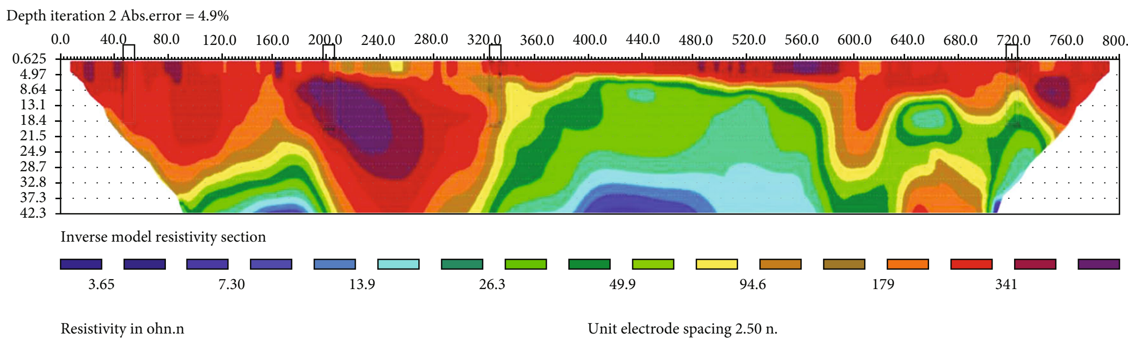


Figure 4: Model of electrical resistivity obtained from the inversion of ERT profile in an east-west direction across the study area. The black boxes from the left to right denote boreholes of 8#, 9#, 10#, and 11#.

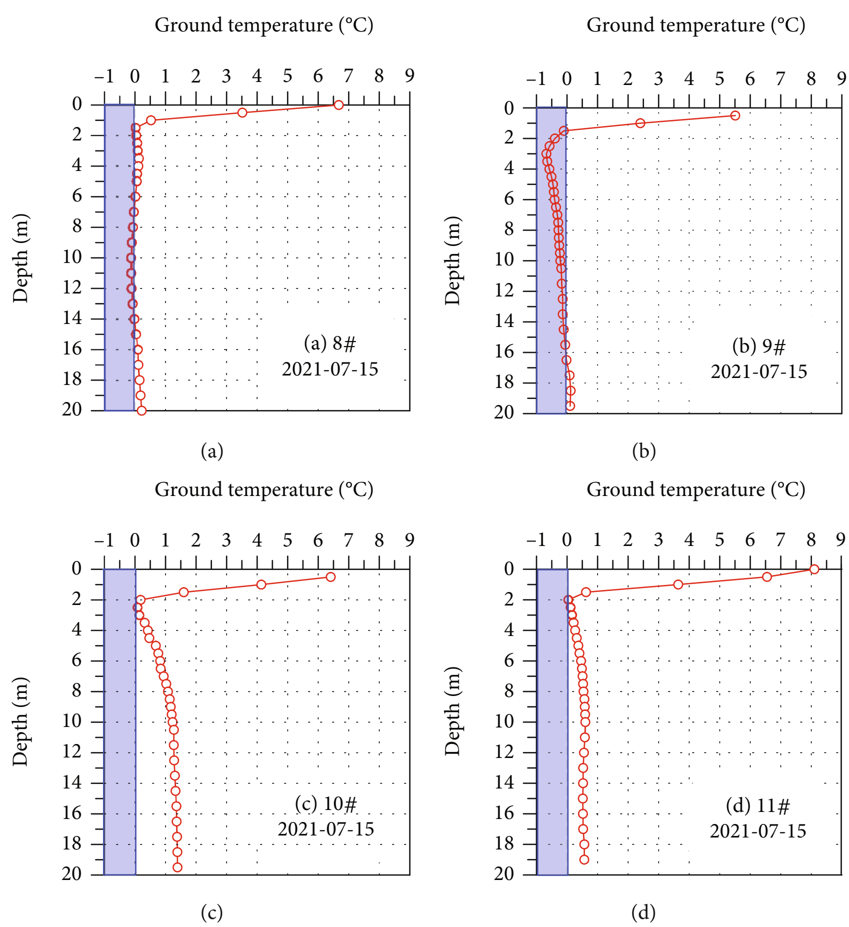


Figure 5: Ground temperature profiles at boreholes of 8#, 9#, 10#, and 11#.

Figure 5, with the same date as the working time of the ERT. From the ground temperature profile of borehole 8#, it can be seen that there is a permafrost layer buried in the depth range of 7 ~ 14 m. Combining with the maximum freezing depth in the study area, it can be initially judged that the permafrost in this part is the relict permafrost. The resistivity near borehole 9# is significantly larger than other areas of the survey line, and the ground temperature profile also clearly reflects the existence of permafrost in the part. The borehole 9# penetrated the permafrost layer. Therefore, combining the ground temperature profile and electrical survey results, the thickness of permafrost near this borehole is about 15 m. The ground temperature profiles of boreholes 10# and 11# show that there is no permafrost and the ground temperatures in the depth range of 10~15 m are between 1.2 and approximately 1.3°C and 0.5 and approximately 0.6°C, respectively.

Comparing the results of the ERT and the ground temperature measurements at the same time, it can be seen that the two have a good agreement in the interpretation of the distribution of permafrost on the survey line, which initially reflects the distribution characteristics of the survey line automatically westward from relict permafrost to patchy permafrost and then to island talik. The reason for the higher soil resistivity in the shallow depth range at the westernmost end of the survey line is closely related to the topography, geomorphology, and lithology of the site. At the westernmost end of the survey line, there exists a mound, the interior of which is mainly wind-deposited fine to medium fine sand layer with a loose and dry structure. The presence of this mound is related to the high resistivity of the stratum.

3.2. Freeze-Thaw Characteristics of Shallow Ground. For the relict permafrost, patchy permafrost, and island talik, from the perspective of permafrost engineering geological investigation, it is also necessary to grasp the freeze-thaw characteristics of the shallow ground, including the starting freezing time, thawing time, maximum freezing/thawing depths, and other characteristic elements. Figures 6–8 give the isothermal lines of ground temperatures at the relict permafrost, patchy permafrost, and island talik from 2020-09-28 to 2021-09-27, a complete natural year, based on the observation data from boreholes 8#, 9#, and 10#, respectively.

As can be seen from Figure 6, the relict permafrost layer in borehole 8# is buried in the depth range of 7 ~ 14 m, with a thickness of about 7 m and a temperature higher than -0.1°C. It is in the zone of violent phase change and belongs to the extremely high-temperature permafrost. The shallow ground begins to freeze in mid-November and reaches a maximum freezing depth of 2.5 ~ 3.0 m in mid-March and begins to thaw at the surface in early May. The freezing period lasts for about 170 days, which is 5.5 months, and the shallow soils completely thaw around June 20. Although it belongs to relict permafrost, it can be seen from the ground temperature process curve that there is still a bottom-up freezing process from near the top of the relict permafrost.

The seasonal freeze-thaw process of the shallow ground at hole 9# is different from that of the relict permafrost at borehole 8#. As can be seen from Figure 7, the ground surface starts to thaw in mid-May and freeze by early November, and the duration of the thawing period is 180 days which is 6 months, with the maximum seasonal thawing depth between 2.5 and approximately 3.0 m. The permafrost base is buried at a depth of about 17 m, so the permafrost thickness is about 14 m. Similarly, the annual average ground temperature of permafrost, which is the mean annual ground temperature at a depth of 10~15 m, is around -0.1°C, which belongs to extremely high-temperature permafrost.

Borehole 10# is located in island talik, and there is no permafrost layer. Since mid-November, the shallow ground begins to freeze, and the freezing depth reaches a maximum of 2.5 ~ 3.0 m in mid-March. The ground surface begins to thaw at the end of April; thus, the freezing period lasts about 170 days which is 5.5 months. What is significantly different from borehole 8# is that the thawing process of the shallow soils in the talik is very rapid; the soils in the seasonal freezing layer completely thaw in less than half a month from the end of April to the beginning of May, which reflects the seasonal freeze-thaw characteristics of the talik that is freezing in a single direction and thawing in dual directions.

3.3. Cause of the Island Talik. The ERT and borehole temperature measurement well reflect the spatial distribution of the permafrost and talik and the seasonal freeze-thaw process of shallow ground in the study area and reflect the complexity of the distribution of the permafrost in the plane and space in the local area. Although there is a thorough talik developed under the river, the talik range is limited to the main stream line, the channel bar, and the low diffuse beach area, and the width of the talik is about 1.2 km. In this paper, the study area is located on the I-stage terrace of the river and outside the range of the penetrating talik. According to the studies on permafrost distribution in the area, it can be determined that the study area belongs to a large area of discontinuous permafrost region, and the talik of which belongs to the island talik.

As mentioned above, the talik in the QTP permafrost area can be divided into tectonic talik, surface water talik, and infiltration-radiation talik according to their causes, among which tectonic talik can be further divided into the tectonic-geothermal talik and tectonic groundwater talik, while surface water talik can be further divided into the river talik and lake talik. There are two important factors for the existence of infiltration-radiation talik; on the one hand, the surface has a strong ability to absorb the solar radiation; on the other hand, the good permeability of the shallow soil is conducive to the infiltration of atmospheric precipitation. This kind of talik is generally developed in the high-temperature permafrost area (with mean annual ground temperature of 0 ~ -1°C), dominated by loose rock layers with good permeability, and the talik area is small [11].

From the topography and geomorphology of the site, the topography of the patchy permafrost section is slightly lower, the surface is an alpine meadow with good vegetation coverage, surface water develops in summer, and the ground is wet, while the topography of the mound in the island talik is slightly higher and the surface is an alpine grassland with sparse vegetation and dry surface. The engineering geological survey borehole reveals that the lithology in the island talik (borehole 10#) can be divided into cultivated soils (layer thickness is 0.2 m), fine sand (layer thickness is 4.3 m), silty clay (layer thickness is 1.5 m), fully weathered silty mudstone (layer thickness is 1.5 m), and fully weathered mud siltstone (layer thickness is 17.7 m), while the lithology in the patchy permafrost section (borehole 9#) can be divided into cultivated soil (layer thickness is 0.3 m), fine sand (layer thickness is 1.3 m), silty clay (layer thickness is 2.4 m), strong weathered silty mudstone (layer thickness is 4.5 m), and strong weathered mud siltstone (layer thickness is 12 m). It can be seen that the quaternary overburden differs significantly between the two sections. The thickness of the quaternary overburden in the island talik section is 4.5 m, and it is mainly fine to medium fine sand, dry and loose in structure. In contrast, the thickness of the quaternary overburden is only 1.6 m in the patchy permafrost section and underneath it is hard-plastic-like silty clay, which is in the transition state with the lower strong weathered mudstone and silty mudstone, and the bedrock is

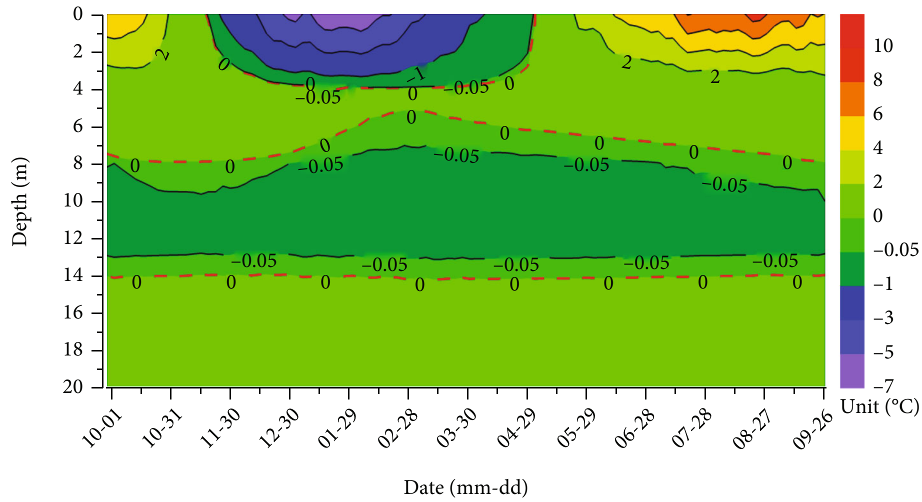


Figure 6: Isothermal lines of ground temperatures at borehole 8#.

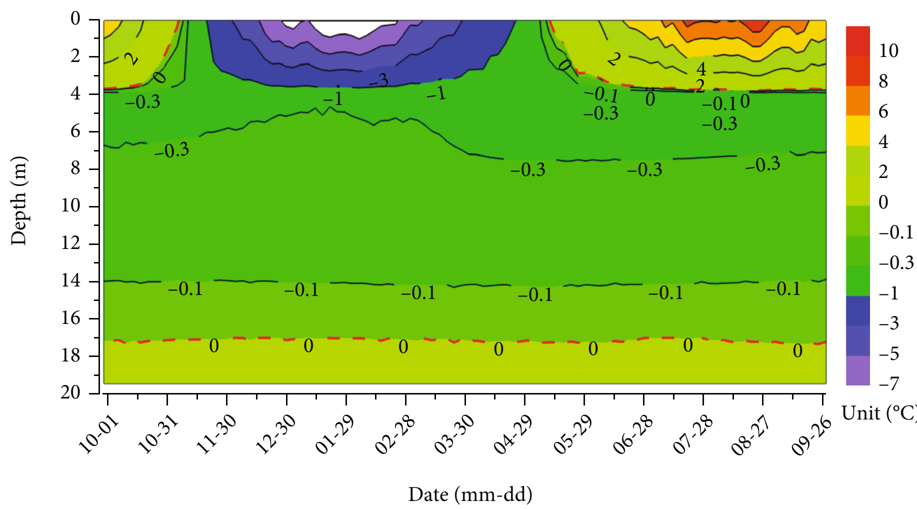


Figure 7: Isothermal lines of ground temperatures at borehole 9#.

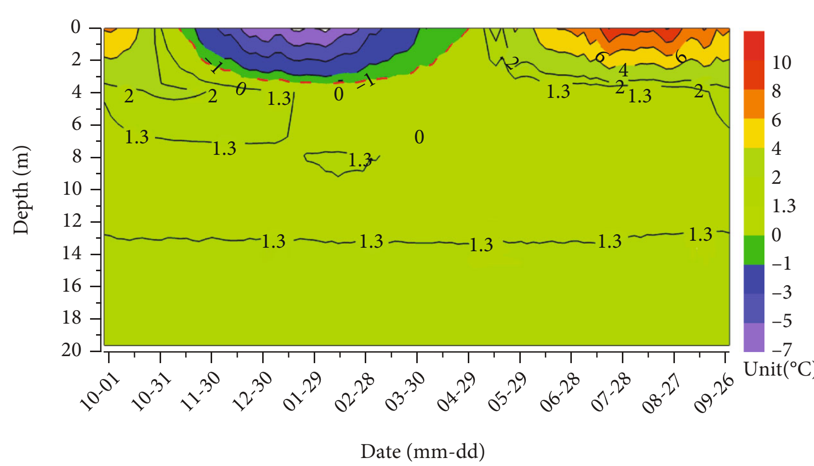


Figure 8: Isothermal lines of ground temperatures at borehole 10#.

shallowly buried. From the viewpoint of groundwater level during the engineering geological investigation, no stable water level is seen in the borehole of the talik section, while the permafrost section is 0.53 m (mid-October). Therefore, combined with the topography, shallow soil lithology, and stable groundwater level, it can be tentatively determined that the island talik in the study area belongs to the infiltration-radiation talik.

4. Conclusion

Compared with conventional thawing soil areas and continuous permafrost areas, the engineering geological investigation of island talik is extremely difficult and uncertain. The continuity and uniformity of hydrothermal conditions of geotechnical bodies in the plane and space are extremely poor, so it is often difficult for a single survey method to meet the needs of engineering construction for investigation work. For the island talik on the I-stage terrace of a river on the Qinghai-Tibet Plateau, based on the field measurement data obtaining from drill prospecting, ERT, and drilling borehole temperature measurement, the spatial distribution of permafrost and the freeze-thaw process of shallow ground in the area were studied in detail, and the causes of the island talik were discussed in combination with the results of existing permafrost distribution studies in the area. The preliminary conclusions are as follows:

(1) Within the limited local range of the study area, three sections were distributed which are the relict permafrost, patchy permafrost, and island talik, and the permafrost distribution is complex in the plane and space. Among them, the embedment depth of the relict permafrost layer is in the range of 7 ~ 14 m, while the patchy permafrost is in the range of 3.0 ~ 17.0 m depth, both of which have a mean annual ground temperature higher than -0.1°C and belong to extremely high-temperature permafrost

(2) The seasonal freezing/thawing depths of shallow ground within the island talik, relict permafrost, and patchy permafrost range from 2.5 to 3.0 m. The freezing period of the overlying seasonal freezing layer of the former two is 5.5 months, while the thawing period of the seasonal thawing layer is 6 months. Both the relict permafrost and patchy permafrost sections have a two-direction freezing process. The two-direction thawing process in the island talik is remarkable; its seasonal freezing layer thaws completely in less than half a month from the beginning of surface thawing, providing a channel for infiltration of summer rainfall

(3) Combined with the topography, stratigraphic lithology, and stable groundwater level in the late warm season, the island talik in the study area is considered an infiltration–radiation-originated talik. The surface of the island talik is covered by an alpine grassland with sparse vegetation, and the quaternary overburden is dry, loose fine to medium fine sand, and the thickness reaches 4.5 m, which is favorable for the infiltration of atmospheric precipitation. The sparse vegetation, dry surface, and wind-deposited sand layer are the important reasons for the formation of the island talik

Through the application of three survey techniques in the field, although the spatial distribution pattern of permafrost has been obtained preliminarily, the meticulousness of the survey results is still insufficient. In the case of plaque-like engineering projects in housing construction category, the spatial distribution of permafrost may have significant differences in different parts of a single body in such sites with complex engineering geological conditions and coupled with the high sensitivity of the physical and mechanical properties of permafrost to temperature in the zone of severe phase change [2]. Such differences in the spatial distribution of permafrost can lead to serious damage to the upper infrastructures if not identified at the survey stage [12].

However, from the actual engineering practice, the survey work is often simply based on relevant codes including permafrost engineering geological survey or housing construction foundation survey to determine the amount of survey work and technical means, while the survey for such complex sites as island taliks often need to determine the workload and technical means while surveying, which should be a dynamic feedback and decision revision process.

Furthermore, from the perspective of engineering construction, operation, and maintenance, the engineering geological survey of island taliks needs to provide engineering designers with the evolution of permafrost in the plane and space within the site under future climate warming and disturbance of engineering activities. However, for such a complex site as island talik, such a task not only involves complex coupling process of permafrost water, heat, and deformation and uncertainty of climate change (temperature and precipitation) but also involves changes of groundwater (water above/beneath the freezing layer) runoff in local ranges, drastic changes of physical and mechanical properties of foundation bearing stratum, and changes of ecological environment, which are a significant challenge for engineering survey practitioners. These are generally significant difficulties for the engineering survey practitioners. Therefore, for the engineering geological investigation of permafrost island taliks, not only the update of survey technology and means is needed but also the support of the development of permafrost engineering-related disciplines. Finally, these need to be reflected in the relevant specification requirements for better guiding the engineering practice.

Data Availability

Those data acquired from field measurement and the detailed introduction can be found in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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