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Seasonal freeze-thaw behavior of ground in mid-latitude cold regions: a case study in Bei'an County, Heilongjiang Province

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seasonally frozen ground, freeze-thaw characteristics, cold regions, ground temperature, Xiao xing'anling mountains

1 Introduction

Frost heave and thaw settlement in cold regions are static problems associated with complex water and thermal processes, and their mechanical states exhibit seasonal variations. Under unfavorable conditions, the deformation caused by freezing and thawing continues to accumulate, ultimately leading to foundation-related issues (Li et al., 2021; Wu et al., 2021; Zhang F. C. et al., 2021; Xu et al., 2021). The frost heave and settlement induced by seasonal freezing and thawing pose a significant threat to the operational safety of foundation engineering in cold regions. To mitigate the effects of freeze-thaw cycles, the main engineering approach is to increase the foundation depth, using the anchoring force of deep foundations to counteract the freeze-thaw effects (Dourado et al., 2024; Wang et al., 2022; Li et al., 2022). However, scientifically determining the appropriate foundation depth relies on precise quantification of depth of seasonal freezing (Zhang X. D. et al., 2021). With global climate warming, depth of seasonal freezing continues to fluctuate (Luo et al., 2019; Gao et al., 2025), presenting new challenges for engineering design in cold regions (Wang and Chen, 2024). It is crucial to understand the freeze-thaw behavior of local soils and accurately measure and quantify the seasonal development of freeze depth to prevent foundation uplift and instability (Shang et al., 2022; Shang et al., 2025). In this context, conducting freeze-thaw characteristic analysis based on field data can help update the key parameters for regional engineering design, ensuring that the design schemes adapt to environmental changes and achieve both safety and economic goals for cold-region infrastructure (Chen et al., 2023).

Bei'an County is situated on the southwestern foothills of the Xiao Xing'anling Mountains and the fringe of the Songnen Plain, characterized predominantly by hilly and mountainous terrain. Located at a mid-to-high latitude, Bei'an County experiences a cold-temperate continental monsoon climate. Due to the complex topography and elevation variations within the region, there are significant climatic differences across localized areas. The vegetation is composed of forest flora, meadow plants, and meadow-steppe species. As a result, the characteristics of seasonally frozen ground in this region are highly specific. Temperature monitoring data of seasonally frozen ground in this area can greatly improve the accuracy of regional freeze-thaw depth zoning (Li et al., 2021). However, there is

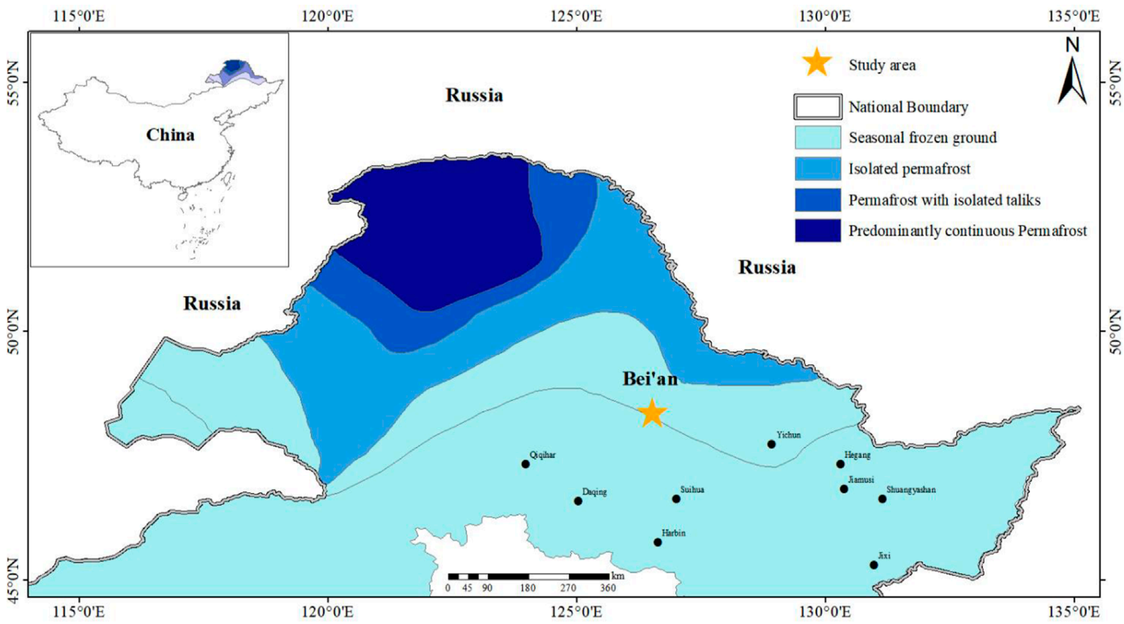

FIGURE 1
Location of experimental site.

limited research on seasonally frozen ground characteristics in this region, with existing monitoring data and studies primarily focusing on the central parts of the Songnen Plain (Tang et al., 2024; Wang et al., 2012; Feng et al., 2019) and the central part of the Xiao Xing'anling Mountains (Hua et al., 2014). Research and monitoring of seasonally frozen ground in their transitional zone, where climatic conditions are more complex, have not been reported. Additionally, existing studies rely on historical monitoring data, highlighting the necessity for updating the seasonally frozen ground characteristic parameters in this region.

In light of this, we conducted field monitoring and provided ground temperature data for Bei'an County from 2023 to 2024. This study presents parameters such as the seasonal freeze-thaw cycle, the development process of freezing depth, and the characteristics of temperature fluctuations. This study can directly guide the design of foundational engineering in cold regions. Additionally, it not only enhances the accuracy of climate models, but also provides critical data support for agricultural management and water resource planning, while offering a scientific basis for monitoring ecosystem health and developing disaster prevention measures.

FIGURE 2
Temperature sensor.

2 Methods

2.1 Study area

Figure 1 shows that the study site is located in Bei'an County, Heilongjiang Province, at approximately 126.9°E longitude and 48.6°N latitude. The site is situated in the transition zone between the Songnen Plain and the southern foothills of the Xiao Xing'anling Mountains, where the topography is predominantly hilly and mountainous. The eastern part of the area is mountainous, with a relatively high elevation, averaging above 400 m; the central

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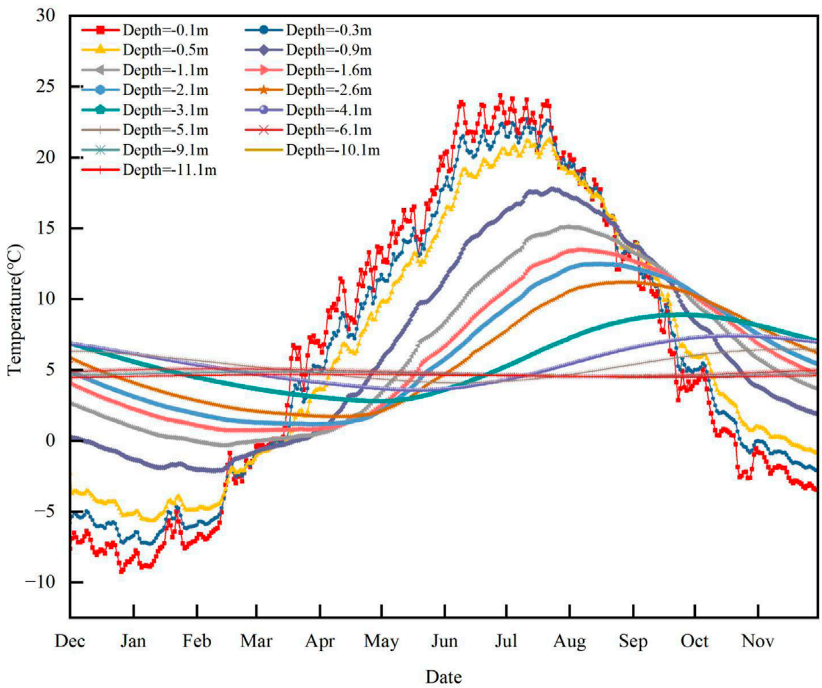

FIGURE 3
Variation of the ground temperature with time at different depths.

TABLE 1 Annual mean temperatures at different depths.

Depth(m)	0.1	0.3	0.5	0.9	1.1	1.6	2.1	2.6	3.1	4.1	5.1	6.1	9.1	10.1	11.1
Temperature (°C)	6.42	6.40	6.37	6.30	6.30	6.15	6.06	6.04	5.96	5.69	5.46	5.27	4.83	4.70	4.59

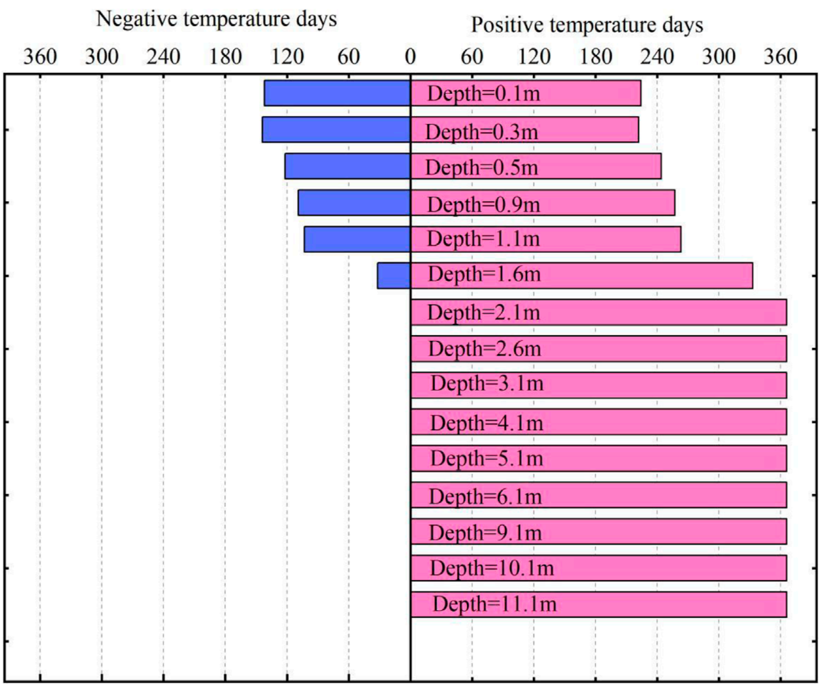

FIGURE 4
Number of days with positive and negative temperatures at different depths.

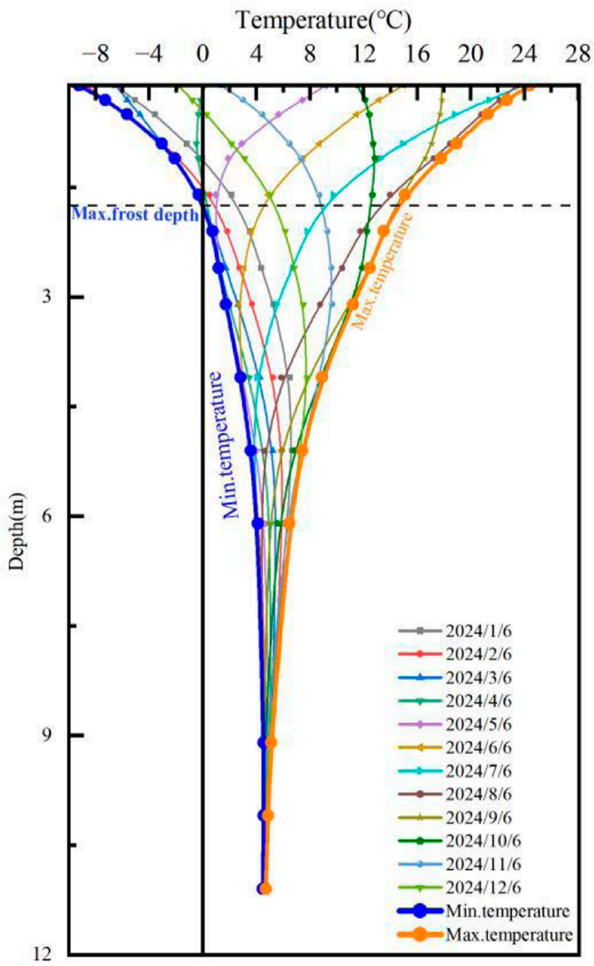

FIGURE 5
Variation of the ground temperature along the depth in different seasons.

region is characterized by hills, with elevations ranging from 300 to 350 m; the western part is a transition zone into the Songnen Plain, with elevations between 250 and 300 m; and the southern region features a relatively gentle terrain, with an average elevation of about 250 m. Overall, the terrain exhibits a pattern of higher elevations in the east and north, and lower elevations in the west and south. The area has a cold temperate continental monsoon climate, with a long-term average annual temperature of 1.2°C, but temperatures are rising year by year as the climate warms (Jin et al., 2007). The frost-free period ranges from 88 to 120 days, and the average annual precipitation is 529 mm. Summers feature long daylight hours, while autumn experiences significant diurnal temperature variation, with rainfall and heat occurring in the same season (Xu et al., 2020).

2.2 Data and methods

Figure 2 shows the temperature sensors calibrated by the State Key Laboratory of Frozen Soils Engineering and Cryospheric Science (China). These temperature sensors are thermistors, and their operation relies on the relationship between resistance and temperature. By utilizing the known temperature-resistance relationship, the resistance value can be converted into temperature for accurate measurement. These sensors, with an accuracy of ±0.05°C, were installed at the study site using a borehole method. The sensors were arranged vertically from the surface to a depth of 11.1 m, with sensor locations at depths of 0.1, 0.3, 0.5, 0.9, 1.1, 1.6, 2.1, 2.6, 3.1, 4.1, 5.1, 6.1, 9.1, 10.1, and 11.1 m below the surface. Temperature data acquisition was performed at 6 h intervals (0:00, 6:00, 12:00, and 18:00 UTC) using a CR6 datalogger (Campbell Scientific Inc.), with measurements automatically recorded and transmitted via autonomous remote telemetry. The temperature sensors were connected to the data acquisition system through the TYMX201 channel solid-state multiplexer produced by Beijing Tiannuo Technology Co., Ltd. The power supply system consisted of photovoltaic panels coupled with rechargeable battery arrays, engineered to maintain continuous operation under harsh cryogenic environments. This configuration ensured stable power delivery for sustained data acquisition cycles while preserving measurement integrity under thermally dynamic frozen soil conditions.

3 Result and analysis

3.1 Ground temperature characteristics

Figure 3 shows the average daily temperature variations at different depths from December 2023 to December 2024. As observed, within the depth range of 0.1–6.1 m below the surface, the ground temperature exhibited significant fluctuations. However, as the depth increased, the temperature fluctuations below 6.1 m became less pronounced. Table 1 presents annual mean temperature values at vertically stratified depths. At a depth of 0.1 m, the highest temperature reached 24.39°C, and the lowest temperature was −9.26°C. January was the coldest month in this region, with an average monthly temperature of −7.59°C at the shallow depth of 0.1 m, while July was the hottest month, with an average monthly temperature of 21.66°C at the same depth.

Figure 4 presents the number of days with positive and negative temperatures at different depths from 2023 to 2024, based on a 366-day period. It can be observed that for the six depths ranging from 0.1 to 1.6 m, the number of days with positive temperatures were 224, 222, 244, 257, 263, and 333, respectively, while the number of days with negative temperatures were 142, 144, 122, 109, 103, and 33, respectively. For depths greater than 1.6 m, the soil temperature remained positive throughout the 366 days. The proportion of days with negative temperatures at depths from 0.1 to 1.6 m relative to the total 366 days were 38.80%, 39.34%, 33.33%, 29.78%, 28.14% and 9.02%, respectively, indicating a gradual decrease in the proportion of negative temperature days with increasing depth.

3.2 Freeze-thaw process

Figure 5 illustrates the variation of ground temperature with depth across different seasons from January 2024 to December

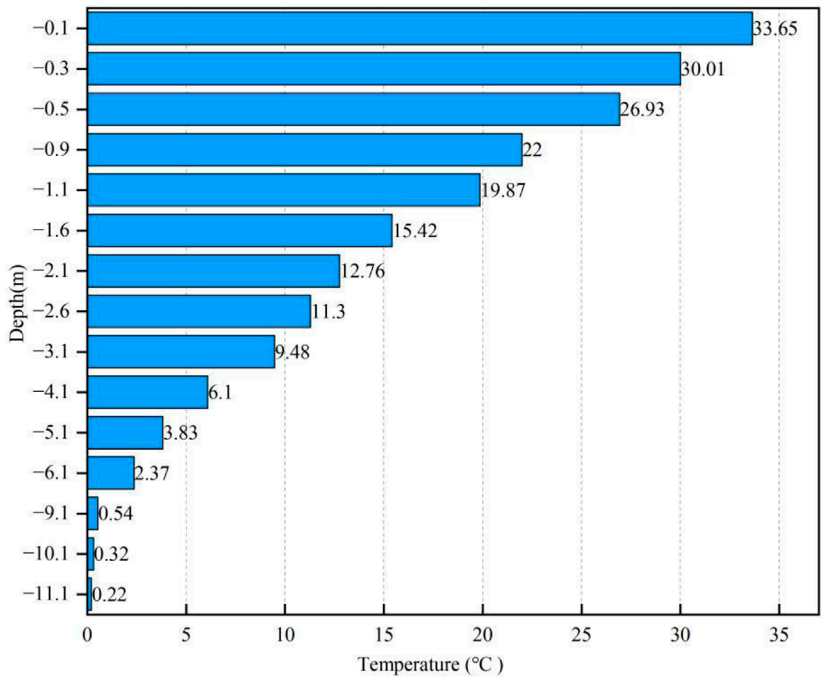

FIGURE 6
Annual range of ground temperature.

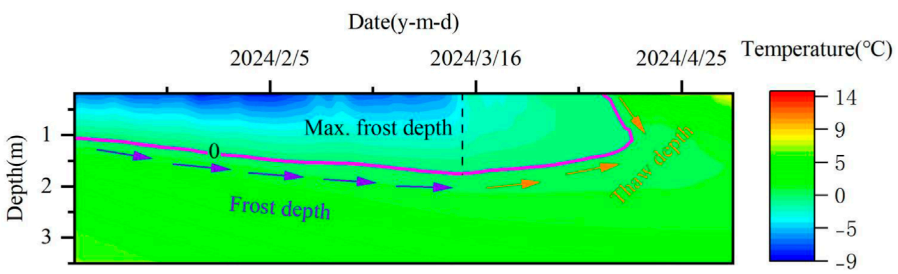

FIGURE 7
Freeze-thaw process from December 2023 to May 2024.

2024. As shown in the figure, the maximum freezing depth in this region was 1.75 m. Within the depth range of 0.1–1.6 m, the soil temperature fluctuated between −9.26°C and 24.39°C over the 12-month period. In the depth range of 1.6–11.1 m, the temperature fluctuated between −0.31°C and 15.11°C throughout the year. Compared to the 0.1–1.6-m depth range, the amplitude of soil temperature fluctuations decreased by 54.18%. Below a depth of 9 m, the temperature fluctuated around 4.5°C.

Figure 6 shows the annual ground temperature variation at different depths. The maximum annual range of ground temperature observed at a depth of 0.1 m was 33.65°C, which decreased significantly to 15.42°C at 1.6 m, marking a 54.18% reduction in amplitude. At a greater depth of 11.1 m, the thermal fluctuation was minimal, registering only 0.22°C, which corresponded to a 99.35% attenuation compared to the surface variability.

Figure 7 shows the freezing process of the soil within the 11.1 m depth range. The study area was located in the mid-latitude seasonally frozen ground regions. As shown in the figure, the maximum seasonal freezing depth during the period from December 2023 to April 2024 reached 1.75 m. Regarding the development of freezing depth, as the freezing process progressed, the maximum freezing depth reached 1.75 m by mid-March, with a freezing rate of 2.3 cm/d, classifying it as middle-thick seasonally frozen ground. Subsequently, as the ground temperature continued to rise, the freezing depth gradually decreased. The figure also illustrates that, starting from 13 March 2024, thawing began from the lower side of the seasonal maximum freezing depth, followed by thawing from the upper side. The thawing was completed by 16 April 2024, with thawing rates of 1.91 cm/d and 2.94 cm/d, respectively.

4 Conclusion

Based on ground temperature monitoring data from December 2023 to December 2024, this study primarily investigated the freezing and thawing characteristics of mid-latitude seasonally frozen soil. The following conclusions were drawn:

1. In terms of the temporal dimension, the soil in this region began freezing in mid-November and completed freezing by mid-March. Thawing was completed by mid-April.
2. By mid-March, the maximum freezing depth of 1.75 m is attained, with a freezing rate of 2.3 cm/d. Thawing began at the lower side of the seasonal maximum freezing depth, followed by thawing at the upper side, with thawing rates of 1.91 cm/d and 2.94 cm/d, respectively.
3. The fluctuation amplitude of annual ground temperature observed at a depth of 0.1 m is 33.65°C, which decreases significantly to 15.42°C at 1.6 m, marking a 54.18% reduction in amplitude. At a greater depth of 11.1 m, the maximum annual range of ground temperature is minimal, registering only 0.22°C, which corresponds to a 99.35% attenuation compared to the surface variability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

WL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Writing–original draft, Writing–review and editing. YS: Data curation, Formal Analysis, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. GL: Methodology, Project administration, Resources, Supervision, Writing–review and editing. KG: Methodology, Project administration, Resources, Supervision, Writing–review and editing. HZ: Funding acquisition, Supervision, Writing–review and editing. JS: Software, Validation, Writing–review and editing.

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Conflict of interest

Authors HZ and JS were employed by State Grid Heilongjiang Electric Power Company Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2025.1566593/full#supplementary-material

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