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Temperature compensation method for static level monitoring system and its application

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Received 27 June 2025
Revised 8 July 2025
Accepted 8 July 2025

Abstract

Purpose – This study solves the key problem that the static level monitoring is susceptible to temperature interference and affects the accuracy in slope instability/deformation monitoring. The purpose is to develop a reliable temperature compensation method for the system, improve the accuracy of slope stability monitoring and provide support for improving the safety and safety monitoring of engineering spoil slope and other projects.

Design/methodology/approach – Combined with theoretical analysis and experimental verification, the temperature compensation method is explored. The working principle of the hydrostatic leveling monitoring system is analyzed and the data processing formula, the temperature error calculation formula and the calculation formula for eliminating the error settlement value are derived. The temperature compensation method is established and verified by the field test of the engineering spoil slope which is disturbed by a debris flow.

Findings – The experimental results show that this method can reduce the error of the static level monitoring system by about 40 %. The field test shows that the fluctuation of slope settlement monitoring value is reduced after temperature compensation and the monitoring value is consistent with the actual situation, which has certain practicability.

Originality/value – The originality of this study is to derive a theoretical formula for quantifying/eliminating temperature errors in static leveling and to establish a practical temperature compensation method. The accuracy of the system is improved, which provides a reference for slope stability monitoring under complex environment (especially railway geotechnical engineering) and promotes the development of precision monitoring technology.

Keywords Engineering spoil, Slope instability, Static level, Temperature error, Model correction

Paper type Research article

Funding: This study was funded by the Scientific Research Project of China Academy of Railway Sciences Group Co., Ltd (No. 2024YJ332 and No. 2024QT005) and Scientific Research Special Project of China State Railway Group Co., Ltd (No. TICSTR-2024-IV-007).

Railway Sciences
Vol. 4 No. 4, 2025
pp. 536-549
Emerald Publishing Limited
e-ISSN: 2755-0915
p-ISSN: 2755-0907
DOI 10.1108/RS-06-2025-0021

1. Introduction

Landslide is a typical phenomenon of slope instability, which may cause secondary disasters such as river blockage and debris flow. With the continuous advancement of China's infrastructure construction, a large number of engineering spoil have been established in the central and western regions. Once the slope of these engineering spoil is unstable, it will cause significant losses to the local ecological environment and people's lives and property. Therefore, it is of great practical value and social benefit to ensure the stability of the slope of the soil and rock engineering spoil field. The static level is a precision instrument for measuring the height difference and its change, which is suitable for monitoring the settlement and uneven uplift of the whole surface of the slope. This plays an important role in effectively evaluating the stability of soil-rock engineering spoil slope and predicting potential unstable events (Mu *et al.*, 2021).

The static level is to measure the pressure difference between the measurement point and the reference point by perceiving the change of ground gravity and using the principle of liquid level balance, so as to determine the settlement deformation of the slope measurement point. However, the static level monitoring technology is susceptible to changes in the external environment at the construction site, resulting in measurement errors. Factors such as tides and gravity anomalies can only be mitigated under constant temperature conditions and their effects are limited to micron scales. Relevant errors can be ignored for non-high-precision monitoring work. At the same time, the installation of isobaric tubes can eliminate pressure difference errors. In the actual slope settlement detection, temperature change is considered to be the most critical factor (Xu, Liu, & Luo, 2018). Domestic and foreign scholars have carried out extensive research on the elimination of temperature error and achieved gratifying results.

Zhang, Zhang, Zhang, Qiu, and Wei (2018) used the vibrating wire static leveling monitoring system to monitor the cumulative settlement of the transmission tower base. By analyzing the relationship between the vibrating wire frequency and temperature, the cumulative settlement data of the vibrating wire static leveling monitoring system was corrected by temperature (Zhang *et al.*, 2018). Quantitatively studied the influence of ambient temperature on the test accuracy of hydrostatic level and further established the correction model of ambient temperature hydrostatic level considering the influence of ranging and expansion coefficient (Bo, Guo, & Qi, 2021). Some researchers proposed a temperature correction model considering the change of ambient temperature and verified the validity of the model in the actual site settlement monitoring (Jia, Cheng, Li, Liu, & Qian, 2021). Lekomtseva and Tsvetkov used theoretical analysis and numerical simulation to establish a method to reduce the degree of fluid temperature inhomogeneity between pipes under the influence of temperature gradient (Lekomtsev & Tsvetkov, 2019).

In summary, scholars have tried to establish the relationship between temperature effect and test error through theoretical analysis, numerical modeling, laboratory test and field test. At the same time, based on the test data, the test error evaluation method caused by temperature effect is proposed. However, most of the existing evaluation methods only focus on the ambient temperature or temperature gradient, but do not verify the temperature compensation method. Most of the research objects are monitoring bridges, tunnels and dams (Mu *et al.*, 2021; Prakash, Dugalam, Barbosh, & Kaneko, 2022; Rizzo & Enshaeian, 2021; Sheikh, Nakata, Shitano, & Kaneko, 2021; Zhou, Zhou, Lu, & He, 2024) and there are few studies on the applicability of slope stability monitoring.

In view of this, this study studies the working principle and data processing method of the hydrostatic level monitoring system through theoretical analysis and establishes the temperature compensation method of the hydrostatic level monitoring system. On this basis, taking the slope of a railway spoil yard as the research object, the temperature compensation method of the static level monitoring system is verified by the temperature compensation method verification experiment of the outdoor static level monitoring system. The reliability of the modified model is verified by field test.

2. The principle of static level monitoring system

2.1 Static level monitoring system

The hydrostatic leveling monitoring system is composed of data acquisition terminal, sensor, power supply and data transmission line, hydraulic line and cloud data server. The purpose of the data acquisition terminal is to send the data collected by the sensor to the cloud data service center. The data acquisition terminal has a built-in wireless transmission module and the monitoring data are transmitted to the cloud data server through the 4G network. The cloud data server analyzes and processes the data, calculates the instant settlement value and the cumulative settlement value.

The sensor is mainly used to measure the liquid pressure at the measuring point and the built-in temperature module is used to monitor the real-time temperature of each sensor. The power supply and data transmission line is mainly composed of four-core cables, two of which are used for sensor power supply and the other two are used for data transmission. The power supply line of the static level monitoring system is to supply power to the data acquisition terminal through an external power supply and then supply power to the sensor through a series of two-core cables. The data transmission line is to transmit the liquid pressure detected by each sensor to the data acquisition terminal through two-core cable and the data acquisition terminal transmits the monitoring data to the cloud data server through the 4G network.

The hydraulic circuit is mainly composed of a liquid pipe and a liquid storage tank. The liquid storage tank and each sensor are connected in series through the liquid pipe to form a connector. It is set that the measuring point where the first sensor connected to the liquid storage tank does not undergo settlement deformation and the settlement value of other measuring points can be determined by the liquid pressure change of the sensor.

There are two kinds of commonly used measuring point arrangement methods for hydrostatic level monitoring system. The first kind is “line” shape arrangement, which requires the liquid storage tank and the first sensor connected to it to be arranged in the area where no settlement occurs. Taking the first measuring point as the reference point, the liquid storage tank and the sensor are connected in series in order to form a “line” shape monitoring network. This kind of arrangement direction is suitable for monitoring smaller areas. The second type is “net” arrangement, which is composed of multiple “line” monitoring networks in parallel. Each “line” monitoring network needs to meet the requirements of the first type of measuring point arrangement. This type of arrangement direction is suitable for monitoring large areas for fine monitoring.

The accuracy of the sensor is inherently correlated with its measuring range, typically reaching a precision of 0.05% of the range. At the same time, the static level monitoring system requires that the maximum height difference between each measuring point and the liquid storage tank does not exceed one half of the range. According to the above principles and the accuracy requirements of the measurement, the appropriate sensor type is selected. The selection of the connecting liquid is mainly based on the historical minimum temperature of the monitoring area and the freezing point of the connecting liquid is required to be lower than the historical minimum temperature of the monitoring area.

2.2 The working principle of hydrostatic leveling monitoring system

The static level monitoring system with “net” shape arrangement is composed of multiple static level monitoring systems with “line” shape arrangement, the monitoring system with “line” shape arrangement is the basic element of the static level monitoring system. The layout scheme of the “line” arrangement of the static level monitoring system is usually shown in Figure 1. It can be seen from Figure 1 that the height of the liquid level in the liquid storage tank is the datum plane and Point N_1 is the arrangement point of the first static level gauge, serving as the reference point of the static level monitoring system. Points N_2 to N_i ($i = 2,3,\ldots, j ,\ldots$) are the 2nd to N-th static level gauge measuring points, respectively.

Assuming that monitoring starts from time t_1 and T_1 is the corresponding weather temperature at this moment, the pressures monitored by the pressure chips of the N_1 to N_i static

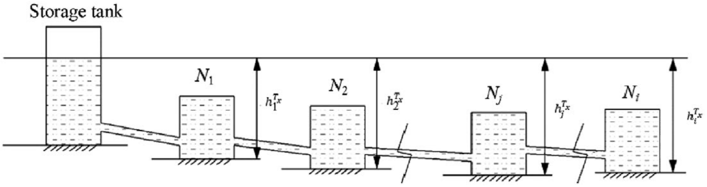


Figure 1. The “line” arrangement of static level monitoring system. **Source(s):** Authors’ own work

level gauges at time t1 are $\rho_{T_1} g h_1^{t_1}, \ldots, \rho_{T_1} g h_i^{t_1}$ (where $h_i^{t_1}$ is the liquid level height of the reference plane relative to the N_i static level gauge at time t_1). The pressure values of the N_1 to N_i static level gauges are converted into water surface elevations corresponding to 4 °C, denoted as $\frac{\rho_{T_1}}{\rho_0} h_1^{t_1}, \ldots, \frac{\rho_{T_1}}{\rho_0} h_i^{t_1}$, which are the initial readings displayed on the cloud platform for each static level gauge. In the initial state (time t_1), the height of the N_i measuring point relative to N_1 is $\frac{\rho_{T_1}}{\rho_0} h_1^{t_1} - \frac{\rho_{T_1}}{\rho_0} h_i^{t_1}$.

From time $\boldsymbol{t_1}$ to $\boldsymbol{t_2}$, the weather temperature changes from $\boldsymbol{T_1}$ to $\boldsymbol{T_2}$. When settlements occur at measuring points $\boldsymbol{N_1}$ to $\boldsymbol{N_i}$, the readings of each measuring point monitored by the static level gauges are $\boldsymbol{\frac{\rho_{T_2}}{\rho_0} h_1^{t_2}}, \ldots, \boldsymbol{\frac{\rho_{T_2}}{\rho_0} h_i^{t_2}}$, (where $\boldsymbol{h_i^{t_2}}$ is the liquid level height of the reference plane relative to the $\boldsymbol{N_i}$ static level gauge at time $\boldsymbol{t_2}$). Since point $\boldsymbol{N_1}$ is the reference point and does not settle, the height of the $\boldsymbol{N_i}$ measuring point relative to $\boldsymbol{N_1}$ in this state is $\boldsymbol{\frac{\rho_{T_2}}{\rho_0} h_1^{t_2} - \frac{\rho_{T_2}}{\rho_0} h_i^{t_2}}$. The instant settlement value of the $\boldsymbol{N_i}$ measuring point at time $\boldsymbol{t_2}$ is as follows:

$$h(t_2, T_2) = \left(\frac{\rho_{T_2}}{\rho_0} h_1^{t_2} - \frac{\rho_{T_2}}{\rho_0} h_i^{t_2} \right) - \left(\frac{\rho_{T_1}}{\rho_0} h_1^{t_1} - \frac{\rho_{T_1}}{\rho_0} h_i^{t_1} \right) \tag{1}$$

From time $\boldsymbol{t_{j-1}}$ to $\boldsymbol{t_j}$, the weather temperature changes from $\boldsymbol{T_{j-1}}$ to $\boldsymbol{T_j}$ when settlements occur at measuring points $\boldsymbol{N_1}$ to $\boldsymbol{N_i}$, the readings of each measuring point monitored by the static level gauges are $\boldsymbol{\frac{\rho_{T_j}}{\rho_0} h_1^{t_j}}, \ldots, \boldsymbol{\frac{\rho_{T_j}}{\rho_0} h_i^{t_j}}$ (where $\boldsymbol{h_i^{t_j}}$ is the liquid level height of the reference plane relative to the $\boldsymbol{N_i}$ static level gauge at time $\boldsymbol{t_j}$). Since point $\boldsymbol{N_1}$ is the reference point and does not settle, the height of the $\boldsymbol{N_1}$ measuring point relative to N1 in this state is $\boldsymbol{\frac{\rho_{T_j}}{\rho_0} h_1^{t_j} - \frac{\rho_{T_j}}{\rho_0} h_i^{t_j}}$. The instant settlement value of the $\boldsymbol{N_i}$ measuring point at time $\boldsymbol{t_j}$ is as follows:

$$h(t_j, T_j) = \left(\frac{\rho_{T_j}}{\rho_0} h_1^{t_j} - \frac{\rho_{T_j}}{\rho_0} h_i^{t_j} \right) - \left(\frac{\rho_{T_{j-1}}}{\rho_0} h_1^{t_{j-1}} - \frac{\rho_{T_{j-1}}}{\rho_0} h_i^{t_{j-1}} \right) \tag{2}$$

Summing the instant settlement $\Delta \boldsymbol{h}(\boldsymbol{t_x}, \boldsymbol{T_x})$ at each moment $\boldsymbol{t_x}$ ($i = 2, 3, \ldots, j$) can obtain the cumulative settlement value of the $\boldsymbol{N_i}$ measuring point from time $\boldsymbol{t_1}$ to $\boldsymbol{t_j}$:

$$\sum h(t_x, T_x) = \left(\frac{\rho_{T_j}}{\rho_0} h_1^{t_j} - \frac{\rho_{T_j}}{\rho_0} h_i^{t_j} \right) - \left(\frac{\rho_{T_1}}{\rho_0} h_1^{t_1} - \frac{\rho_{T_1}}{\rho_0} h_i^{t_1} \right), x = 2, 3, \ldots, j \tag{3}$$

Where $\boldsymbol{\rho_0}$ is the density of the connecting liquid at 4°C and $\boldsymbol{\rho_{T_j}}$ is the density of the connecting liquid at temperature $\boldsymbol{T_j}$.

3. Temperature compensation method of hydrostatic leveling monitoring system

Assume that from time $\boldsymbol{t_1}$ to $\boldsymbol{t_k}$, the $\boldsymbol{N_i}$ measuring point does not undergo settlement, while the ambient temperature changes from $\boldsymbol{T_1}$ to $\boldsymbol{T_k}$. Then, according to Equation (3), the observed cumulative settlement value of the $\boldsymbol{N_i}$ measuring point can be calculated as:

$$\sum h(t_x, T_x) = \left(\frac{\rho_{T_k}}{\rho_0} h_1^{t_k} - \frac{\rho_{T_k}}{\rho_0} h_i^{t_k}\right) - \left(\frac{\rho_{T_1}}{\rho_0} h_1^{t_1} - \frac{\rho_{T_1}}{\rho_0} h_i^{t_1}\right), x = 2, 3, \ldots, k \qquad (4)$$

Since the $\boldsymbol{N_i}$ measuring point does not undergo settlement, which means $\boldsymbol{h_1^{t_k} - h_i^{t_k} = h_1^{t_1} - h_i^{t_1}}$, Equation (4) can be further simplified as:

$$\sum h(t_x, T_x) = \frac{\rho_{T_k} - \rho_{T_1}}{\rho_0}\left(h_1^{t_1} - h_i^{t_1}\right), x = 2, 3, \ldots, k \qquad (5)$$

Equation (5) is the error value of the cumulative settlement of the $\boldsymbol{N_i}$ measuring point caused by the influence of ambient temperature from time $\boldsymbol{t_1}$ to $\boldsymbol{t_k}$. The difference between the observed cumulative settlement value and the error value is the true cumulative settlement value of the $\boldsymbol{N_i}$ measuring point from time $\boldsymbol{t_1}$ to $\boldsymbol{t_k}$ and the calculation formula is as follows:

$$\sum h(t_x, T_x) = \sum h(t_x, T_x) - \sum h(t_x, T_x) = \frac{\rho_{T_k}}{\rho_0}\left[\left(h_1^{t_k} - h_i^{t_k}\right) - \left(h_1^{t_1} - h_i^{t_1}\right)\right], x = 2, 3, \ldots, k \qquad (6)$$

It can be seen from formula (6) that the temperature error is caused by the change of the density of the connected liquid caused by the temperature change, which leads to the change of the pressure monitored by the pressure chip monitored by each static level. In the static level monitoring system, when the external temperature changes, the liquid endothermic or exothermic process takes a period of time, resulting in the liquid temperature is not synchronized with the external temperature. Therefore, the temperature has a delay effect on the slope settlement value based on the static level monitoring and the delay time of each sensor is different.

To determine the delay time of the settlement error caused by temperature, the cumulative settlement data and temperature data of the N_i measuring point within one day are selected and the variation curves of temperature data and cumulative settlement data with time are analyzed. The time interval t_m between the peak of the temperature data and the peak of the cumulative settlement is obtained, which is the delay time of the static level gauge at the N_i measuring point. The calculation formula for the true cumulative settlement value of the N_i measuring point considering the delay effect from time t_1 to t_k is as follows:

$$\sum h(t_x, T_x) = \frac{\rho_{T_{k-m}}}{\rho_0}\left[\left(h_1^{t_k} - h_i^{t_k}\right) - \left(h_1^{t_1} - h_i^{t_1}\right)\right] x = 2, 3, \ldots, k \qquad (7)$$

4. Validation of temperature compensation method for static level monitoring system

In order to analyze the error of slope settlement value based on temperature correction method, a static level monitoring system was installed in an outdoor monitoring area without settlement in August 2024 and 55 % ethylene glycol aqueous solution was selected as the connecting liquid to carry out the temperature compensation method verification experiment of the outdoor static level monitoring system. The curve of the density of 55 % ethylene glycol aqueous solution with temperature is shown in Figure 2.

Due to there is no settlement of the slope, the cumulative settlement value monitored by the static level monitoring system is the measured error value. The monitoring data of the static level monitoring system of the test point was selected for analysis on August 22, 2024. Through formula (3), the curve of the actual monitoring value with time including the temperature error can be calculated (see the blue curve in Figure 3). The curve of temperature error with time can be calculated by formula (6) (see the red curve in Figure 3). The change curve of the actual monitoring value with time after eliminating the temperature error can be calculated by formula (7) (see red curve in Figure 4).

It can be seen from Figure 3 that there is the same trend between the measured error value and the theoretical error value caused by temperature. It can be seen from Figure 4 that the

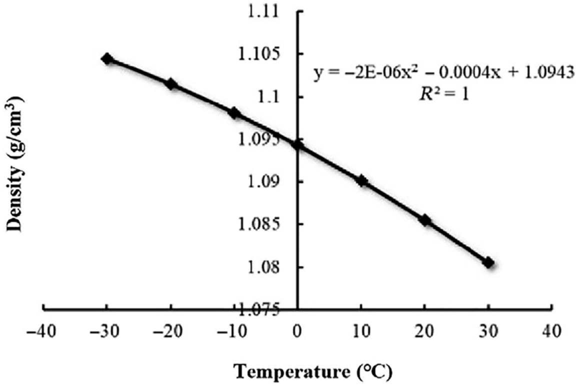


Figure 2. Density curve of 55% ethylene glycol solution with temperature. **Source(s):** Authors' own work

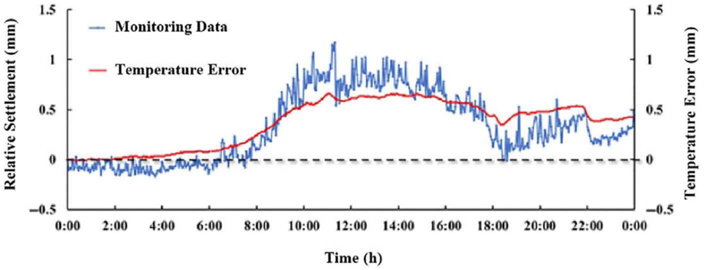


Figure 3. Relation between measuring point error and temperature of static leveling monitoring system. **Source(s):** Authors' own work

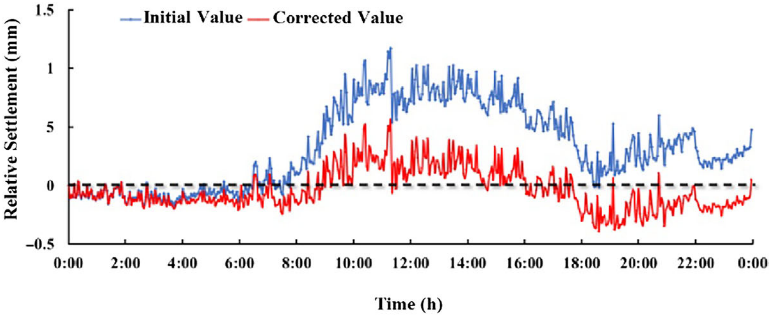


Figure 4. Static leveling monitoring system measurement point error before and after temperature compensation. **Source(s):** Authors' own work

fluctuation range of the monitoring value of the static level monitoring system before the temperature correction is −0.168 mm to 1.173 mm and the fluctuation range is 1.341 mm. After the temperature correction, the fluctuation range of the actual cumulative settlement value is −0.248 mm to 0.561 mm, the fluctuation range is 0.809 mm and the fluctuation is reduced by 40 %. It can be shown that the temperature compensation method of the hydrostatic leveling monitoring system is effective and correct. The temperature compensation method of the hydrostatic leveling monitoring system can reduce the error of the hydrostatic leveling monitoring system by 40%.

5. Application of temperature compensation method for static level monitoring system

5.1 On-site environmental conditions and the layout of the monitoring system

The large engineering spoil slope along a railway line is affected by debris flow erosion, resulting in the damage of the accumulated steps and a large number of debris flows are mixed with the original spoil, resulting in the spoil dump as an unstable accumulation body. The engineering spoil slope is facing a huge hidden danger of instability, which seriously threatens the safety of field personnel and equipment (Figure 5). In order to study the characteristics of the deformation of the engineering spoil field and make early warning of its instability, it is particularly important to monitor the deformation of the slope toe of the abandoned engineering spoil.

In this study, the slope toe of the spoil field was selected as the slope instability monitoring area. Due to the timely detection of the slope foot of the spoil field after being destroyed by the debris flow, the surrounding deformation has not been greatly expanded. In addition, the height difference at the damaged slope toe is small (about 1.2 m). Therefore, 12 static level monitoring points (N1 to N12, where N1 is the reference point) are arranged on the site and their coordinates are shown in Table 1. Sensors with a measurement range of 0m to 1.5m were selected for N1 to N10 monitoring points and sensors with a measurement range of 0m to 2.5m were selected for N11 to N12 monitoring points. Through the query of historical meteorological data, it can be seen that the minimum temperature of the engineering spoil

Figure 5. The slope of engineering spoil after the erosion of debris flow. **Source(s):** Authors' own work

Table 1. The local coordinates of the 12 static level gauge monitoring points

	Local coordinates (m)		
	X	Y	Z
N_1	−1127.401	662.675	3044.951
N_2	−1121.444	634.443	3044.859
N_3	−1117.991	619.567	3044.871
N_4	−1131.947	636.607	3044.898
N_5	−1144.433	648.545	3044.968
N_6	−1150.966	640.856	3045.070
N_7	−1161.108	624.873	3045.263
N_8	−1170.802	607.091	3045.409
N_9	−1190.186	590.989	3045.273
N_{10}	−1197.168	573.346	3045.019
N_{11}	−1224.031	556.528	3043.865
N_{12}	−1245.365	538.033	3043.812

Source(s): Authors' own work

site in the region is −10 °C. In order to prevent the interlinked liquid from freezing in winter, 55 % ethylene glycol aqueous solution with a freezing point of −40 °C was selected as the interlinked liquid. The curve of the density of the connected liquid with the ambient temperature is shown in Figure 2.

In this study, the SD-226 sensor was selected and its operating temperature was determined to be in the range of −40 °C to 85 °C and its operating voltage was between 7 and 12V (DC). The monitoring accuracy of the SD-226 sensor is 0.2 mm. In addition, the sensor provides automatic, uninterrupted monitoring and collects surface subsidence data every 5 minutes. Taking the first monitoring point as the reference point, the linear monitoring network is adopted. Twelve SD-226 sensors were installed in the main part of the slope toe of the engineering spoil, using polypropylene (PPR) pipes to avoid the effects of wind-induced vibration.

5.2 Monitoring results

5.2.1 Analysis of original monitoring results. In this study, 288 cumulative subsidence and 288 temperature readings were collected from each monitoring point every day. In order to directly reflect the variation characteristics of surface cumulative settlement and ambient temperature with time, the average value of 288 cumulative settlement data and 288 temperature data is used to replace the cumulative settlement and temperature of the day. From September 26, 2024 to November 6, 2024, the cumulative settlement value change curve of the monitoring point N2 to N12 is shown in Figure 5. As shown in Figure 6, the variation characteristics of cumulative settlement can be divided into three categories. The first category includes monitoring points N2 to N6 (Figure 6). During the monitoring period, the cumulative surface solidification rate fluctuated between-2mm and 2.5mm. The second category includes monitoring points N7 to N9 (Figure 6). With the passage of time, the cumulative settlement value increased continuously, reaching 3.9mm, 6.4mm and 5.4mm, respectively, on November 26, 2024. The third category consists of monitoring points N10 to N12 (Figure 6). During the monitoring period, the cumulative set value of the monitoring point N10 fluctuated between-2 mm and 6 mm and the cumulative set value of the monitoring point N11 and N12 fluctuated between −8 mm and 1 mm.

The monitoring results of this study are automatically calculated by the cloud server. In order to confirm whether the principle of the cloud server to calculate the cumulative settlement is consistent with the theory proposed in this paper, the original data are used to calculate the theoretical settlement value of the monitoring point N2 to N12 on September 26

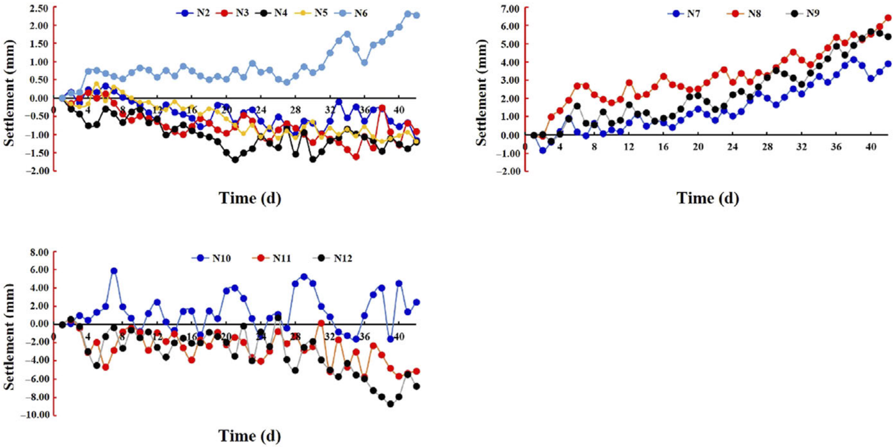
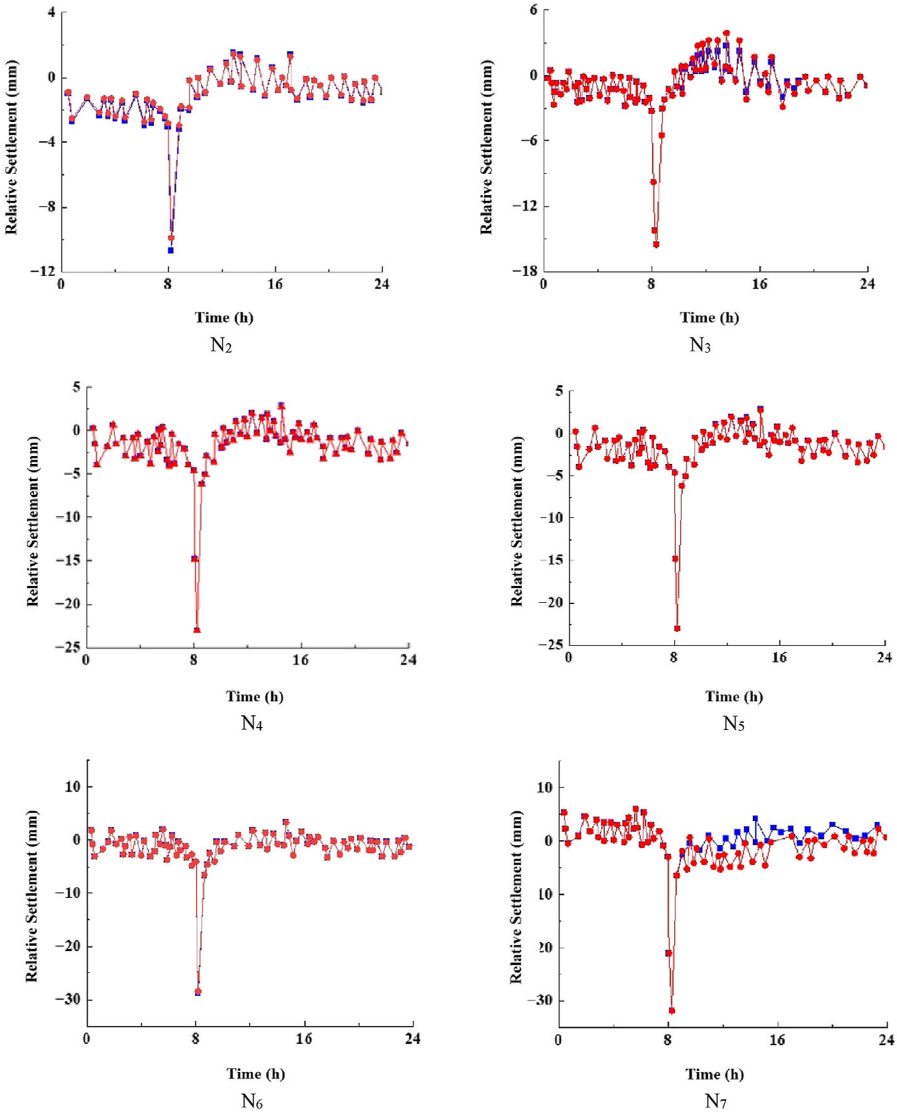


Figure 6. Raw monitoring results. **Source(s):** Authors' own work

using formula (1). Then the theoretical settlement value of monitoring points N2 to N12 is compared with the actual monitoring settlement value and the results are shown in Figure 7. It shows that the theoretical settlement values of monitoring points N2 to N12 have the same change trend and value as the actual monitoring settlement values, indicating that the principle of automatic calculation of cumulative settlement by high-frequency system is consistent with the principle of high-frequency system theory proposed in this study.

5.2.2 Relationship between original settlement and ambient temperature. This study also analyzed the relationship between the original settlement value and the ambient temperature from September 26, 2024 to November 6, 2024 and the results are shown in Figure 8. The results show

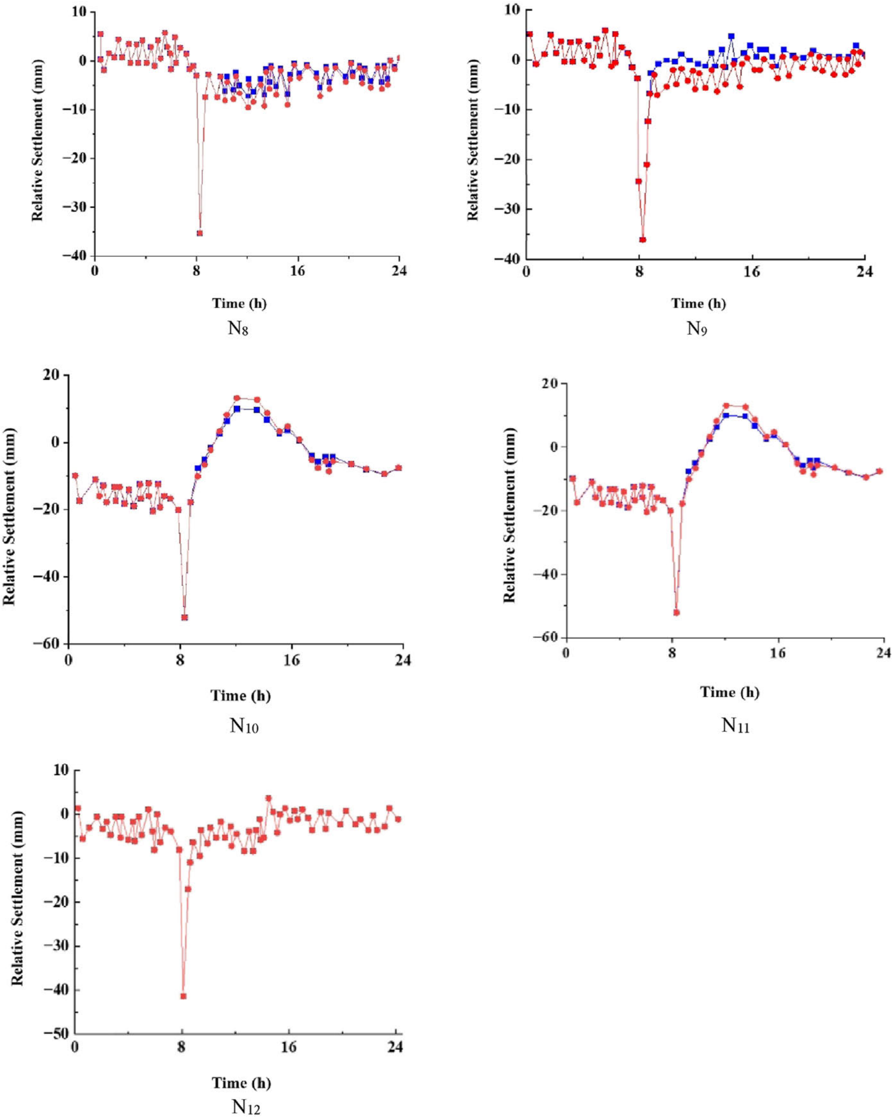


N2 N3

N4 N5

N6 N7

Figure 7. Comparison and analysis results of theoretical settlement value and monitored settlement value (red curve is the theoretical calculated value, blue curve is the measured value). **Source(s):** Authors' own work



N8

N9

N10

N11

N12

Figure 7. (*continued*)

that the cumulative settlement values of monitoring points N2 to N5, N11 and N12 are positively correlated with the ambient temperature, while the cumulative settlement values of monitoring points N6 to N10 are negatively correlated with the ambient temperature. The reason for this phenomenon is that the elevation of monitoring points from N2 to N5, N11 and N12 is lower than that of reference point N1, while the elevation of monitoring points from N6 to N10 is higher than that of reference point N1. Therefore, it can be inferred that the cumulative settlement of the original monitoring results is mainly due to the error caused by the change of ambient temperature.

The cumulative settlement and ambient temperature data on October 13, 2024 are selected below to determine the delay of each monitoring point. The results are shown in Figure 9.

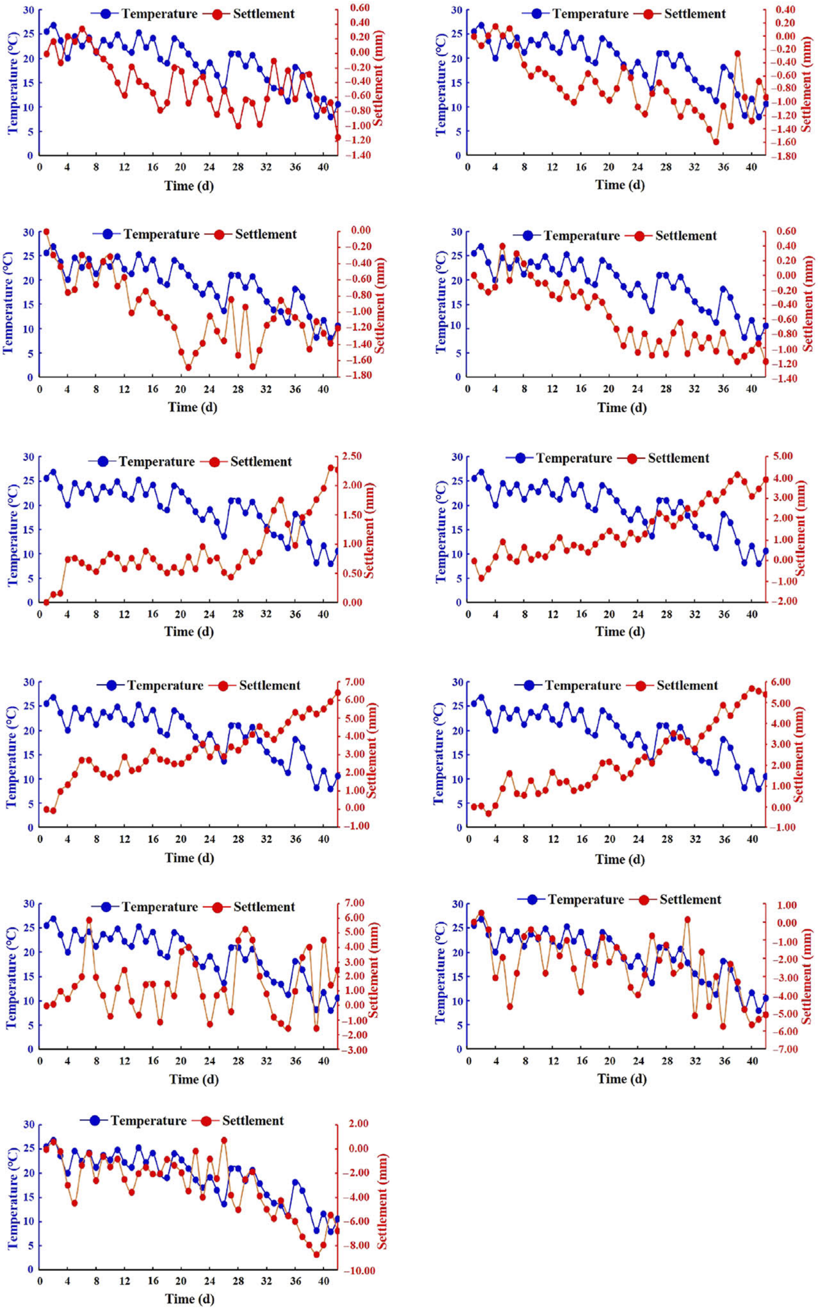
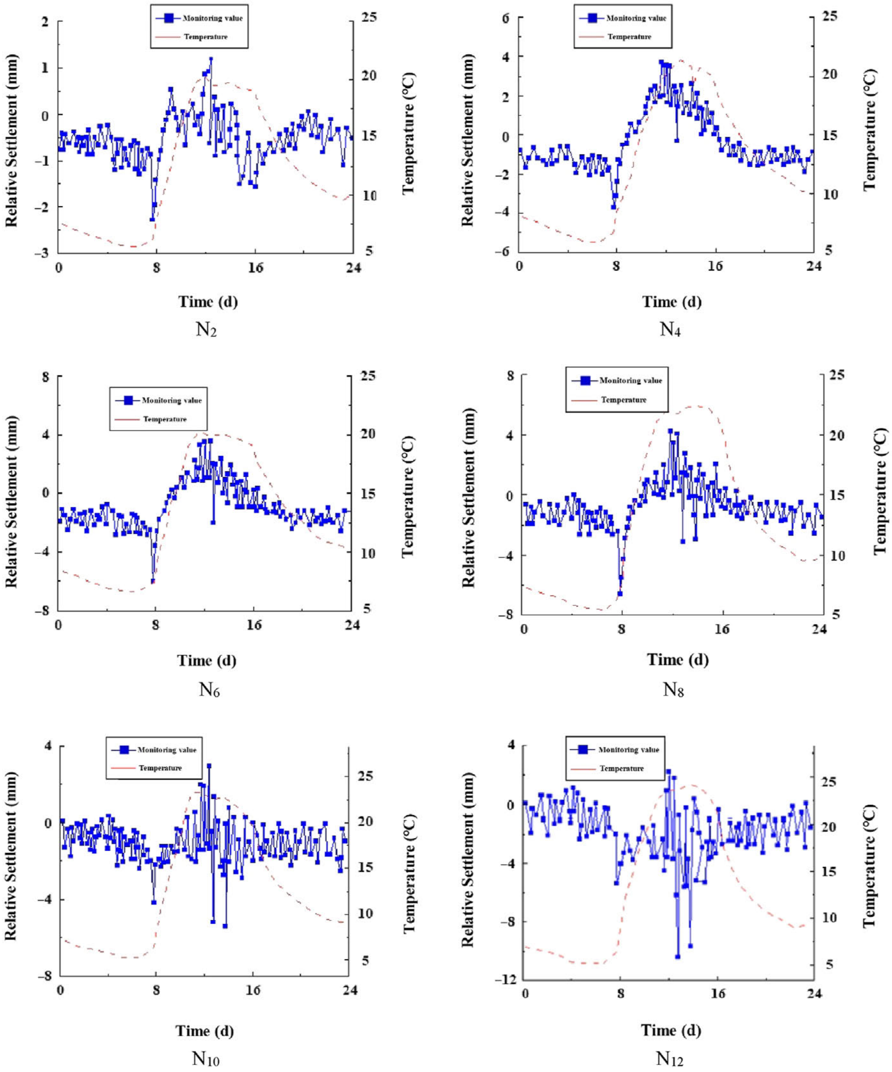


Figure 8. Relationship between original monitoring results and ambient temperature (red curve is temperature change, blue curve is original monitoring results). **Source(s):** Authors' own work



N2 N4

N6 N8

N10 N12

Figure 9. Analysis of time delay effect between monitoring results and ambient temperature (red curve is temperature change, blue curve is original monitoring results). **Source(s):** Authors' own work

The cumulative settlement of monitoring points N2 to N12 began to increase at eight o'clock. In addition, there is no obvious delay phenomenon at the monitoring point N2 to N10. Because the temperature fluctuation in the monitoring area is almost negligible, the time delay effect can be ignored in the long-term cumulative settlement analysis.

5.2.3 Analysis of monitoring results after temperature compensation. According to formula (7), after the temperature compensation of the original monitoring results, the results are shown in Figure 10. It can be seen that, from Figure 10 that the cumulative settlement value of monitoring points N2 to N6 fluctuates between-1mm and 1mm; the cumulative settlement value of N7 to N9 fluctuates between −1.5mm and 1.5mm; and the cumulative settlement value of N10 to N12 fluctuates between −2mm and 2mm. Compared with the original data

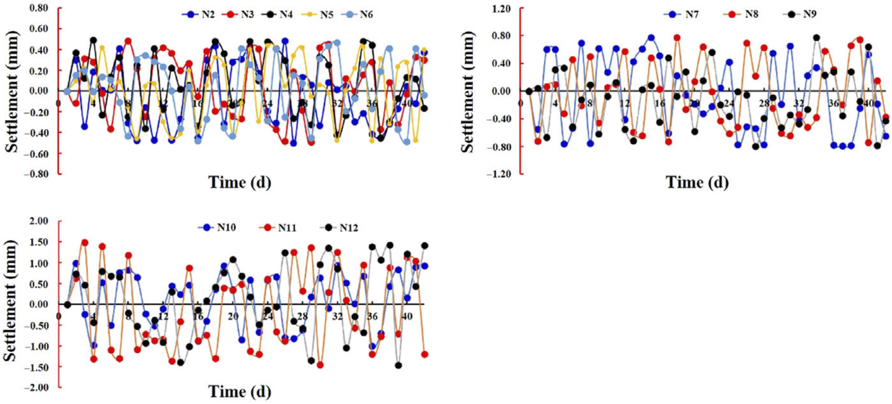


Figure 10. Monitoring results after temperature compensation. **Source(s):** Authors' own work

before temperature compensation, it can be found that the fluctuation range of the cumulative settlement value of the monitoring point after temperature compensation is significantly reduced compared with the fluctuation range of the cumulative settlement value of the monitoring point before temperature compensation. It can be seen from Figure 10 that there is no obvious settlement deformation at the monitoring points from N2 to N12, which is consistent with the actual situation on site.

6. Conclusions

In summary, the key issue of this study is that the static level monitoring is seriously affected by temperature in slope instability and deformation monitoring, which affects its accuracy. Through the combination of theoretical analysis and experimental verification, the working principle of the hydrostatic leveling monitoring system is analyzed, the relevant formulas are deduced and the temperature compensation method is established. The effectiveness of the method is verified by the indoor test and the field test of the spoil field slope after the erosion of a debris flow. The main conclusions are as follows:

(1) Through the analysis of the working principle of the hydrostatic leveling monitoring system, the general formula of the system data processing, the theoretical calculation formula of the cumulative settlement error caused by the temperature change and the calculation formula of the cumulative settlement value after eliminating the temperature error are derived. The temperature compensation method of static liquid level monitoring system is established.

(2) The effectiveness and accuracy of the temperature compensation method are verified by outdoor experiments. The results show that the static level monitoring system with temperature compensation method can effectively reduce the system error by about 40 %. It has achieved good results in the settlement measurement of the slope of the spoil field after the erosion by a debris flow, which provides new technical support for the stability monitoring of the slope of the soil-rock spoil field.

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