Research Article

Experimental Investigation on the Influence of Ambient Temperature on the Test Accuracy for the Differential Pressure Hydrostatic Levelling System

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Hydrostatic levelling system (HLS) is widely used to monitor the settlement of major projects, such as high-speed railways, bridges, tunnels, dams, and nuclear power plants; ambient temperature is the most important influencing factor in the actual engineering settlement detection process. In order to systematically study the influence of ambient temperature T_A on the test accuracy of the HLS, a test platform was built in the ambient temperature laboratory, and the influence of factors, including the amount of T_A change, the rate of increase/decrease of T_A , the expansion coefficient of the connecting pipe, and the distance of the measuring point, on the HLS test accuracy was quantitatively analyzed. The test results show that the elevation of a single HSL case has a linear correlation with the ambient temperature; when the temperature rise rate is greater than $0.1^\circ\text{C}/\text{min}$, the measured data are distorted due to incomplete development of material expansion. The temperature influence coefficient of a single HSL case is linearly related to the expansion coefficient deviation between the refrigerant and pipe; the test error of the double HLS case caused by T_A is attributed to the expansion coefficient deviation of the pipe and the refrigerant between the base station and the measuring point. The relative temperature influence coefficient increases as distance measurement increases, and the HLS test error caused by T_A will maintain a constant value when the distance measurement exceeds a certain value.

1. Introduction

With the rapid socioeconomic development and urbanization, major national infrastructure projects, such as high-speed railways, large-span bridges, ultralong tunnels, high-rise buildings, integrated pipeline corridors, and dams, are increasing; their uneven settlement, deformation, and foundations are a precursor to the engineering failure [1, 2]. Therefore, the accurate measurement for the settlement or deformation is crucial and can provide a scientific reference for the design, construction, and operation of major foundation projects; moreover, reliable data for numerical engineering analysis and long-term deformation prediction can be provided [3–5].

Settlement monitoring methods include geometric levelling, trigonometric levelling, GPS measurement, CCD

optical imaging measurement, laser convergence measurement, hydrostatic levelling, and fibre grating measurement [6, 7]. Among them, geometric levelling and trigonometric levelling are costly and inaccurate; besides, they are limited by topographical fluctuations and challenging to realize real-time monitoring [7, 8]. The accuracy of GPS measurement for plane relative positioning has reached $0.1\text{--}1 \times 10^{-6}$, but its elevation measurement accuracy is only 10^{-2} , which cannot meet some projects' accuracy requirements, and GPS is expensive [9]. Although the CCD optical imaging sensors, laser convergence sensors, and fibre grating sensors have the advantages of high accuracy, strong modality to the terrain, and a high degree of automation [10], the construction and maintenance costs are relatively high, and their anti-interference performance is poor [6]. Because of the simple

structure, high accuracy, strong stability, and little influence from the external environment [11], hydrostatic levelling is widely used in the subsidence monitorization of major projects such as subways [12, 13], bridges [14], tunnels [11, 15–18], dams, and nuclear power plants [19].

The basic principle of the hydrostatic levelling system (HLS) is the liquid connector, which means that, by measuring the relative change of the liquid level in the levelling bowl at different positions, the settlement or uplift of each monitoring point relative to the base point can be determined [19]. However, the accuracy of the HLS is disturbed by factors, including temperature changes, pressure differences, earth tides, and gravity anomalies. [20]. Among them, the earth tides and gravity anomaly can only be filtered under constant temperature, and their influence can be ignored for nonprecision engineering because of the micron-level effect. The influence of pressure difference can be eliminated using equal-pressure pipes. In actual engineering, the temperature change is considered the most important influencing factor during settlement detection. Chen Jihua [21] thought that the uneven temperature would lead to uneven liquid density in the HLS, which leads to the test error; he also proposed a preliminary approach to eliminate temperature impact. Xu Shaofeng [22] investigated the influence of temperature and pressure change on the accuracy of HLS testing and proposed a temperature correction model considering the pipe's expansion coefficient. By installing a temperature sensor in the magnetostatic level bowl, Li Deqiao [9] analyzed the influence of temperature on HLS testing accuracy and verified the temperature correction model proposed by Xu Shaofeng. Based on field test data, Chen et al. [2] proposed a temperature gradient model, and it is suitable for the HLS test system.

In summary, there have been preliminary studies on temperature-induced HLS test errors, but it needs to be noted that most current research studies only focused on a single HLS case, and the temperature changes are concentrated in the order of 10^{-1} [17, 18]. However, during actual settlement monitoring, the annual ambient temperature basically varies from -10 to 30°C . In addition, the existing temperature correction model, based on the water medium, no longer has practical engineering significance, especially in the subzero state; also, there are certain differences in the HLS measuring point spacing arrangement and pipe materials in the actual project.

In this paper, a differential pressure hydrostatic levelling platform was built in the ambient temperature laboratory to systematically study the impact of ambient temperature on HLS testing accuracy. The high-precision temperature sensor was used to collect the temperature data, the change of T_A , the increase/decrease rate of T_A , the expansion coefficient of the connecting pipe, and the distance of the measuring point on the HLS testing accuracy which is quantitatively analyzed. Furthermore, an evaluation method for the influence of ambient temperature on the HLS testing accuracy was developed.

2. Test Platform Construction and Test Program

2.1. Test Equipment and Materials. The Rosemount 3051S differential pressure hydrostatic levelling system was selected in this test because of the advantages of high sensitivity, wide frequency, lightweight, small size, and reliable operation, and its technical parameters are shown in Table 1. The platinum resistance temperature sensor was used to measure the ambient temperature. In order to ensure that the signals of the HLS and temperature sensor can be collected simultaneously and avoid time lag, a full-function collect instrument was selected. The closed-loop controlled ambient temperature chamber in the State Key Laboratory of Materials-Oriented Chemical Engineering of Nanjing Technology University was used to control the temperature changing rate and temperature difference. This equipment can precisely and linearly control the ambient temperature in the range of -40 – 150°C with a fluctuation of less than 0.1°C . The detailed performance parameters of the test chamber are shown in Table 2.

Because the liquid medium of “deionized water + antifreeze” is likely to cause flocculation at low-temperature conditions and the thermal expansion coefficient of water increases with the increase of temperature, dimethicone was selected as the liquid medium in this test. The density of dimethicone is 1.03 g/cm^3 (20°C), and its effective operating temperature range is -60 – 160°C ; the expansion coefficient in the operating temperature range is basically fixed at the value of 6.3×10^{-4} . To study the influence of the expansion coefficient of different connecting pipe materials on the HLS test accuracy, four kinds of connecting pipes with different expansion coefficients, including PU plastic pipe, polypropylene pipe, PTFE pipe, and 204 stainless steel pipe, were selected. The corresponding expansion coefficients are 3.35×10^{-4} , 1.32×10^{-4} , 1.45×10^{-4} , and 6.43×10^{-5} , respectively.

2.2. Test Platform Installation. Figure 1 shows the layout of the test platform. It can be seen that, in the ambient temperature test chamber, all HLS liquid pipes are connected, and one end is connected to the liquid storage tank; besides, all air pipes are connected, and one end is connected to the upper air section of the tank through a drying pipe. It should be pointed out that the pressure difference of a single HLS measuring point comes from the difference between the liquid pressure and the air pressure, which is an absolute value; the liquid/gas pressure difference between the HLS datum point and the test point is used to calculate the relative settlement between the measured point and the datum point, which is a relative value. The RT-1Q temperature sensor was arranged next to every HLS measuring point, and then the output signal of the HLS and temperature sensor can be collected by the VW-102E full-function reader. The technical parameters of the RT-1Q temperature sensor are shown in Table 3.

TABLE 1: Technical parameters of the Rosemount 3051S hydrostatic levelling system.

Index	Value
Input voltage	24 Vdc
Input current	200 mA
Power	0.9 W
Output current (signal)	4–20 mA
Effective pressure range	0–60 kPa
Effective operating temperature	–50–65°C

TABLE 2: Ambient temperature test chamber parameter performance index.

Index	Value
Temperature range (°C)	–40–150
Temperature fluctuation (°C)	<0.1
Temperature rising rate (°C/min)	<3–5
Temperature falling rate (°C/min)	<0.7–1.5
Temperature sensor	Platinum resistance PT100

2.3. Test Scheme. The influence of the ambient temperature on the test accuracy of the HLS usually can be reflected by the measurement error caused by temperature change. Considering the complex change of the annual ambient temperature of the detected structure, especially in winter and summer, two types of test platforms, including single HLS case (only single differential pressure hydrostatic levelling point) and double HLS cases (test base station + test point), were built in a laboratory with the standard ambient temperature to study the influence of the change of T_A (–10°C → 30°C → –10°C) and the rate of increase/decrease of T_A on the accuracy of HLS test quantitatively. At the same time, combined with the actual engineering conditions and the environmental temperature change, the influence of the connecting pipe length between the base station and the test point (the distance between the test points) and the expansion coefficient of the connecting pipe (with obvious material differences) on the HLS test accuracy was comprehensively considered. The test conditions are shown in Table 4.

3. Test Results and Analysis

3.1. The Influence of the Ambient Temperature Rising/Falling Mode on the HLS Test Accuracy. In order to investigate the influence of the rising/falling mode of the ambient temperature on the HLS test accuracy, by converting the vertical pressure of the liquid medium, the settlement difference of case C1 caused by the temperature rising and falling was compared and analyzed. At the beginning of the test, the settlement of the HLS was recorded as zero for the convenience of analysis.

It can be seen from Figure 2 that, as ambient temperature T_A linearly increased from –10°C to 30°C, the corresponding settlement H_E of the HLS linearly decreased to 3.04 mm; when T_A linearly decreased from 30°C to –10°C, H_E linearly rose from 3.04 mm to 0.03 mm. The temperature influence coefficient $P_t = \Delta H_E / \Delta T_A$ was defined to quantitatively

characterize the effect of ambient temperature on the HLS test accuracy; under the rising/falling mode of case C1, P_t of the HLS was –0.0774 mm/°C and –0.0731 mm/°C, respectively, and their relative deviation was 5.8%, indicating that the rising or falling mode of ambient temperature had no significant effect on P_t .

3.2. The Influence of Temperature Rising Rate on the HLS Test Accuracy. Because these two ambient temperature changing modes have no significant effect on P_t , there is no need to conduct the falling mode test for cases C2, C3, and C4. Figure 3 shows the influence of the rising rate of temperature on the test accuracy of the single HLS. When the rising rate was 0.05 and 0.02°C/min, H_E and T_A of the HLS were strongly linearly correlated, and P_t of cases C1 and C4 was –0.0774 mm/°C and –0.0777 mm/°C, respectively. When the rising rate was 0.1°C/min, H_E decreased as T_A increased, but it needs to be noticed that the linear correlation between T_A and H_E was significantly weakened, and the data fluctuation became large. When the rising rate was 0.2°C/min, as T_A linearly increased, H_E increased with a decreasing rate. When $T_A > 10^\circ\text{C}$, H_E nearly did not increase as T_A increased; this is because the excessive rising rate of ambient temperature led to the incomplete expansion of materials and liquid media, resulting in data distortion and failing to reflect the impact of T_A on the HLS test accuracy.

The relationship between P_t and the temperature rising rate is shown in Figure 4. Combined with Figure 3, it can be seen that when the temperature rising rate was 0.02 or 0.05°C/min, the HLS worked normally, and P_t was consistent. When the rising rate was greater than or equal to 0.1°C/min, the material expansion was not complete, and the data were distorted. In general, the temperature reached the lowest at 0 a.m., and the temperature reached the highest at 13:00. The maximum temperature difference during this period basically did not exceed 30°C. Therefore, under natural conditions, the temperature changing rate was less than 0.04°C/min. Besides, considering the effectiveness of data collection and the test progress, the temperature changing rate was decided to be 0.05°C/min for other test cases.

3.3. The Influence of Pipe Expansion Coefficient on the HLS Test Accuracy. In order to investigate the influence of the pipe expansion coefficient γ_{pi} on the single HSL test accuracy, a series of single-point test platforms were built with the PU plastic pipe, PTFE pipe, polypropylene pipe, and 204 stainless steel pipe, respectively. The test was carried out under a temperature rising rate of 0.05°C/min. As shown in Figure 5, H_E decreased linearly with the increase of T_A for PU plastic pipes, while H_E increased linearly with the increase of T_A for PTFE pipes, polypropylene pipes, or 204 stainless steel pipes. This is because γ_{pi} of PU plastic pipes is greater than that of dimethicone, and the liquid level of simethicone decreased with the increase of T_A , leading to a decrease in elevation; by contrast, for PTFE pipes, polypropylene pipes, and 204 stainless steel pipes, γ_{pi} is obviously

FIGURE 1: Schematic diagram of the working layout for the typical hydrostatic levelling system.

TABLE 3: Technical parameters of the RT-1Q temperature sensor.

Index	Value
Effective operating temperature	$-40\sim 80^{\circ}\text{C}$
Level of sensitivity	$\pm 0.005^{\circ}\text{C}$
Temperature measurement accuracy	$\pm 0.01^{\circ}\text{C}$
Water pressure resistance	$\geq 0.5\text{ MPa}$
Insulation resistance	$\geq 50\text{ M}\Omega$
Storage humidity	$\leq 80\%\text{ RH}$
Storage temperature	$-30\sim 70^{\circ}\text{C}$

smaller than that of dimethicone, and the liquid level of simethicone rose with the increase of T_A , increasing H_E .

Furthermore, it was found that smaller γ_{pi} would not deliver the influence of T_A on the single HSL measuring point. It is necessary to study the relationship between P_t and the difference between the liquid medium expansion coefficient γ_{di} and the pipe expansion coefficient γ_{pi} . As shown in Figure 6, P_t increased with the increase of $\gamma_{di}-\gamma_{pi}$, showing a linear relationship.

$$P_t = 0.04553(\gamma_{di} - \gamma_{pi}) - 0.0103. \quad (1)$$

It can be known that if γ_{pi} and γ_{di} are close, the influence of T_A on the test accuracy of the single HSL measuring point can be ignored.

In order to study the effect of γ_{pi} on the double HSL test accuracy, the double HSL measuring point test platform was built with PU plastic pipes, PTFE pipes, and polypropylene pipes; HSL was used as a base station, and the other one was used as the measuring point. The test was carried out under the temperature raising rate of $0.05^{\circ}\text{C}/\text{min}$. Figure 7 shows the test data of the base station and the measuring point for case C8. It can be seen that H_E of the base station and the measuring point increased with T_A , but the increasing rate of the elevation of the base station was apparently less than that of the measuring point, and P_t presented a significant difference, which was $0.213\text{ mm}/^{\circ}\text{C}$ and $0.231\text{ mm}/^{\circ}\text{C}$, respectively.

Figure 8(a) shows the relative elevation ΔH_E between the base station and the measuring point caused by T_A 's increasing for case C8. The relative temperature influence coefficient ΔP_t is defined as the difference in P_t between the

base station and the measuring point. For case C8, ΔP_t was $0.018\text{ mm}/^{\circ}\text{C}$, which is significantly smaller than that of C1–C7, suggesting that the measurement error caused by T_A on the “liquid medium box-connecting pipe-base station” did not affect the relative elevation between the base station and the measuring point. The elevation difference was caused by the expansion difference between the connecting pipe and the refrigerant that connects the base station and the measuring point. Figures 8(b) and 8(c) show ΔH_E between the base station and the measuring point for cases C9 and C10, which was caused by the increase of T_A . Similar to the single test point results, for polypropylene pipes, ΔH_E increased with T_A but decreased for PU plastic pipes. However, similar to case C8, ΔP_t of cases C9 and C10 was also obviously smaller than that of the single-point test, and when the connecting pipe was a PU plastic, ΔP_t was negative. It should be pointed out that although the connecting pipe material had a significant effect on ΔP_t , it was related to the length of the connecting pipe between the base station and the measuring point combined with the test results of cases C1–C9.

3.4. The Effect of Measuring Distance on the HLS Test Accuracy.

According to the analysis above, when the connecting pipe material was fixed, the test error of the double or multiple HSL measurement points, which was induced by T_A changing, was mainly determined by the distance of the measurement points. To systematically explore the effect of the distance between measurement points D_{test} (the length of the connecting pipe) on the test accuracy of double HSL test points, PTFE pipes were used to construct the double measurement points' test platform, and the distance between the base station and the test point was set as 0.5 m, 1 m, 5 m, and 10 m. Figure 9 shows the relationship between ΔH_E and T_A . It can be seen that when D_{test} increased to 1 m and 5 m, ΔH_E also increased with the increase of T_A , but under the same T_A , the larger D_{test} was, the larger ΔH_E was, which was consistent with the test results of case C8. Besides, ΔP_t of the double HLS test points was significantly smaller than P_t of the base station under each working condition.

Figure 10 shows the relationship between D_{test} and ΔP_t ; ΔP_t increased with the increase of D_{test} . However, the increasing rate

TABLE 4: The influence of ambient temperature on the measurement accuracy of the HLS.

ID	Test platform	Pipe material	D_{test} (m)	T_A (°C)	T_A rate (°C/min)	Test purpose
C1	Single HLS	PU plastic pipe	—	-10→30→-10	0.05	The effect of temperature rising/falling rate on the HSL test error
C2					0.1	
C3					0.2	
C4					0.02	
C5	Single HLS	PU plastic pipe	—	-10→30	0.05	The effect of pipe material on the single HSL test error
C6		204 stainless steel pipe				
C7		Polypropylene pipe				
C8	Double HLS	PTFE pipe	0.5	-10→30	0.05	The effect of pipe material on the double HSL test error
C9		Polypropylene pipe				
C10		PU plastic pipe				
C11	Double HLS	PTFE pipe	1	-10→30	0.05	The effect of measuring distance on the single HSL test error
C12			5			
C13			10			

FIGURE 2: The influence of temperature rise/fall rate on the measurement accuracy of the HLS. (a) Ambient temperature rising. (b) Ambient temperature falling.

FIGURE 3: Continued.

FIGURE 3: The influence of temperature rise rate on the measurement accuracy of the single HSL test point. (a) Case C1. (b) Case C4. (c) Case C2. (d) Case C3.

FIGURE 4: The relationship between temperature influence coefficient and temperature rise rate.

FIGURE 5: Continued.

FIGURE 5: The influence of pipe expansion coefficient on the measurement accuracy of the single HSL test point. (a) PU plastic pipe. (b) PTFE pipe. (c) 204 stainless steel pipe. (d) Polypropylene pipe.

FIGURE 6: The relationship between the temperature influence coefficient and the expansion coefficient deviation between the refrigerant and pipe.

FIGURE 7: The relationship between ambient temperature and elevation of the base station and test point HSL for case C8. (a) Base station. (b) Measuring point.

FIGURE 8: The relative elevation between the base station and test point HLS versus ambient temperature for cases C8–C10. (a) PTFE pipe. (b) Polypropylene 204 pipe. (c) PU plastic pipe.

FIGURE 9: The relationship between relative elevation and ambient temperature under different measuring distances. (a) Case C8. (b) Case C11. (c) Case C12. (d) Case C13.

of ΔPt appears gradually decreased, and it can be inferred that when D_{test} exceeds a certain value, ΔP_t may be maintained at a fixed value, but under larger D_{test} conditions, the precise

environmental temperature control is difficult to be achieved due to the limited test conditions. D_{test} and ΔP_t present a power function relationship as follows:

FIGURE 10: The relationship between measuring distance and relative temperature influence coefficient.

$$\Delta P_t = 0.054 - 0.0236D_{\text{test}}^{-0.617}. \quad (2)$$

Incorporating with the definition of ΔP_t , under the ambient temperature considering the influence of D_{test} , the ambient temperature evaluation model of the HLS measuring points can be established:

$$\begin{aligned} \text{Set}_{\text{true}} &= \text{Set}_{\text{test}} - \Delta H_E, \\ \Delta H_E &= (0.054 - 0.0236D_{\text{test}}^{-0.617}) \times \Delta T_E, \end{aligned} \quad (3)$$

where Set_{true} is the actual settlement of each HLS measuring point to eliminate the influence of temperature effect and Set_{test} is the test settlement of each HLS measuring point.

4. Conclusions and Discussion

In this paper, a test platform with differential pressure hydrostatic levelling was installed in the ambient temperature laboratory. The high-precision temperature sensors were adopted to collect the temperature of each measurement point of the HLS, and the influence of factors, such as the ambient temperature, the increasing/decreasing rate of the ambient temperature, the expansion coefficient of the connecting pipe, and the distance of the measuring point, on the HLS test accuracy was quantitatively analyzed. The relevant conclusions can be drawn as follows:

- (1) The elevation of the single HSL measuring point showed a single correlation with the ambient temperature. When the ambient temperature increasing rate was 0.02 or 0.05°C/min, the ambient temperature influence coefficient was consistent, and the test results were valid. When the increasing rate was greater than or equal to 0.1°C/min, the material expansion was not complete, and the data were distorted.
- (2) The single HSL measuring point's temperature influence coefficient was linearly related to the difference in the expansion coefficient between the liquid medium and the pipe. When the expansion coefficient of the selected pipe was close to the expansion coefficient of the liquid medium, the effect of the temperature on single HSL test accuracy can be ignored.

- (3) The test error of the double HLS measuring points caused by ambient temperature was attributed to the expansion difference between the connecting pipe and the liquid medium. The connecting pipe material and the length of the connecting pipe had a significant effect on the relative temperature influence coefficient.
- (4) The relative temperature influence coefficient increased with the increase of the measurement distance, while the increase rate of the relative temperature influence coefficient gradually decreased, which preliminarily indicated that when the measurement distance exceeded a certain value, the HLS test error caused by the environmental temperature basically remains constant.

Data Availability

The data are generated from experiments and can be made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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