

A NOVEL METHOD FOR EARTH PRESSURE DISTRIBUTION MEASUREMENT VIA THE THERMO-MECHANICAL RESPONSE OF FLEXIBLE CUSHIONS

Lin Zhao^{1,2)}, Zhengyi Zeng^{1,2)}, Jiang Chen^{1,2)}, Ling He³⁾

1) MOE Key Laboratory of Deep Earth Science and Engineering, Sichuan University, Chengdu 610065, China
(✉chxifei@126.com)

2) Failure Mechanics and Engineering Disaster Prevention Key Laboratory of Sichuan Province, Sichuan University, Chengdu 610065, China

3) W2 Architecture x Structural Engineering Ltd, Sydenham, Christchurch 8023, New Zealand

Abstract

The compression deformation of a flexible cushion will lead to a decrease in thermal resistance. Based on this characteristic, a surface heat source method for earth pressure monitoring was proposed in this paper. In this method, a surface heat source, a heat-conducting plate, a flexible cushion, and a temperature sensing array were sequentially placed on the surface of the structure under test. The pressure distribution can be identified by monitoring the temperature response on the outer surface of the flexible cushion after the surface heat source was electric heated. Firstly, a series of calibration tests were conducted on two kinds of flexible cushions made of polyurethane sponge pad and silicone foam board under uniform compression. A dimensionless pressure discrimination index κ was defined based on the heating law on the outer surface of the flexible cushion, and the calibration relationship between pressure and κ was established. The effects of thickness and material properties of flexible cushion on the measurement sensitivity and range were also studied. Then, a polyurethane sponge pad was used as flexible cushion to conduct a series of verification tests under 9 loading conditions. Subsequently, the pressure distributions were identified using the aforementioned calibration relationship between pressure and κ . The results show that the pressure distribution identification results were basically consistent with the actual loading situations, thus verifying the feasibility of the method proposed in this paper.

Keywords: earth pressure, thermal resistance, fiber Bragg grating, temperature tracer method, geof foam.

1. Introduction

Earth pressure represents the predominant load on supporting and underground structures, thereby serving as a pivotal factor in the design scheme of such structures. Meanwhile, the stability assessment of structures such as retaining walls, deep foundation pit supports, tunnel linings, and slope engineering directly depends on the accurate judgment of earth pressure distribution patterns. Consequently, the study of earth pressure is a pivotal subject in the field of

geotechnical engineering [1, 2]. Earth pressure measurement serves as a crucial verification tool for the accuracy of earth pressure calculation theories, compensating for their inherent limitations. It is a fundamental technical approach to investigating the earth pressure distribution.

The earth pressure cell is the most commonly used transducer for earth pressure measurement and is widely used in geotechnical engineering practice and scientific research. For diaphragm-type earth pressure cells, the stiffness of the elastic diaphragm is often significantly lower than that of the soil, leading to underestimated measurements. However, the stiffness of the elastic diaphragm is generally correlated with the sensor's sensitivity, and increasing the diaphragm stiffness would reduce sensitivity, making it unable to meet engineering requirements [3]. On the other hand, steel earth pressure cells typically have a stiffness much higher than that of the soil, resulting in overestimated readings. Furthermore, the shape and size of the sensor can also introduce errors in earth pressure monitoring [4]. In order to improve the accuracy and reliability of earth pressure monitoring data, it is often necessary to calibrate the earth pressure cell according to the measured soil and working environment [5–8]. Earth pressure is a surface load and, when the measurement range is extensive, this point-type measurement device must be buried with more sensors, which results in increased costs and amount of monitoring cables. In the past few decades, *fiber Bragg grating* (FBG) technologies have developed rapidly. These technologies boast several advantages, including distributed measurement and electromagnetic-interference immunity [9, 10]. These characteristics enable it to compensate for the limitations of point-type measurement technology, such as its narrow coverage, susceptibility to electromagnetic interference, and other defects. Additionally, the thin nature of fiber optics facilitates miniaturization, making it a suitable material for the development of miniature earth pressure sensors [11].

Temperature change, as a ubiquitous physical driving factor, can produce significant coupling effects with various physical quantities. By leveraging such coupling effects, other physical quantities can be indirectly identified by measuring the patterns of temperature response. This method is referred to as the temperature tracer method [12] and has been extensively studied in measurement fields such as soil moisture content [13, 14], seepage velocity [15, 16], concrete cover thickness [17], crack localization and width [18–20], foundation scour depth [21, 22], and pile integrity assessment [23].

Placing an *expanded polystyrene* (EPS) inclusion between a rigid retaining wall and the backfill induces lateral displacement in the backfill, transitioning the lateral earth pressure from the at-rest state toward the active state. This mechanism effectively reduces the lateral load on the retaining wall, thereby optimizing the design of rigid retaining structures [24, 25]. Meanwhile, the reduction in thickness of the flexible cushion under compression also leads to a decrease in thermal resistance. Thus, this coupled thermo-mechanical effect provides the theoretical foundation for the research on the novel earth pressure measurement system presented in this paper. The measurement system is instrumented with an FBG temperature sensor array on the exterior surface of the flexible cushion behind the retaining wall. By monitoring the heating pattern of the array and leveraging the thermo-mechanical coupling effect, the distribution of earth pressure is inferred. The measurement model, established through calibration, was subsequently verified.

2. Principle and measurement system

When heat is transferred inside an object by thermal conduction, the heat transfer mechanism is related to the thermodynamic properties of the surrounding medium. Thermal resistance reflects the ability of a material to impede heat transfer and it is obvious that the magnitude of the coefficient of thermal resistance directly correlates with the material's efficacy in obstructing heat

conduction. When heat flows through the cross-sectional area of a constant flat plate, the thermal conductivity resistance can be expressed as:

$$R_c = \frac{L}{kA}, \quad (1)$$

where L is the thickness of the plate, A is the cross-sectional area of the plate perpendicular to the direction of heat flow, k is the thermal conductivity of the plate material.

As shown in Fig. 1, when a flexible cushion is subjected to pressure, the thickness of its pressure influence range will be reduced. If the flexible cushion is a porous material, the porosity will also be reduced after being pressurized, which will lead to an increase in the thermal conductivity, as shown in (2).

$$k_p = \phi k_a + (1 - \phi)k_s, \quad (2)$$

where k_p is the equivalent thermal conductivity of porous material, ϕ is the porosity of the porous material, k_a and k_s are the thermal conductivities of air and solid phase of the porous material, respectively.

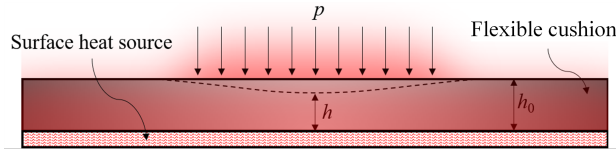


Fig. 1. Deformation patterns of the flexible cushion under pressure.

In sum, when the flexible cushion made of porous material is subjected to pressure, not only is the thickness of the cushion reduced but also its equivalent thermal conductivity is increased, thus reducing the thermal resistance of the flexible cushion. In the presence of a surface heat source on the bottom surface of the flexible cushion, the application of pressure leads to a reduction in thermal resistance. Therefore, the heat released by the surface heat source is more readily transferred upward, thereby accelerating the temperature rise rate of the top surface of the flexible cushion. Consequently, in the context of a surface heat generation set on the bottom surface of a flexible cushion, the magnitude of the applied pressure could be indirectly measured by monitoring the temperature variation on the top surface of the flexible cushion.

Based on the fundamental principles of the surface heat source method for earth pressure measurement, taking the earth pressure monitoring of a retaining structure as an example, the monitoring scheme shown in Fig. 2 was designed. On the stress-bearing surface of the retaining wall, a heating pad (surface heat source), a heat-conducting plate, and a flexible cushion (which can cover the entire area or be laid only in local regions) were sequentially installed. A temperature sensor array was then arranged at specific intervals on the outer surface of the flexible cushion.

The heating pad can utilize a silicone heating pad with densely distributed resistance wires. The heat-conducting plate serves to accelerate the in-plane heat transfer from the heat source, ensuring more uniform temperature distribution across the surface, and can employ materials such as aluminium or copper plate. The flexible cushion should exhibit excellent elasticity, with its hardness and thickness selected according to the required measurement range and sensitivity of earth pressure. The temperature measurement system must demonstrate high precision, sensitivity, and long-term stability, suitable for large-scale temperature monitoring. An FBG temperature sensor system is recommended for this purpose, meanwhile, it is necessary to use the FBG demodulator for the test.

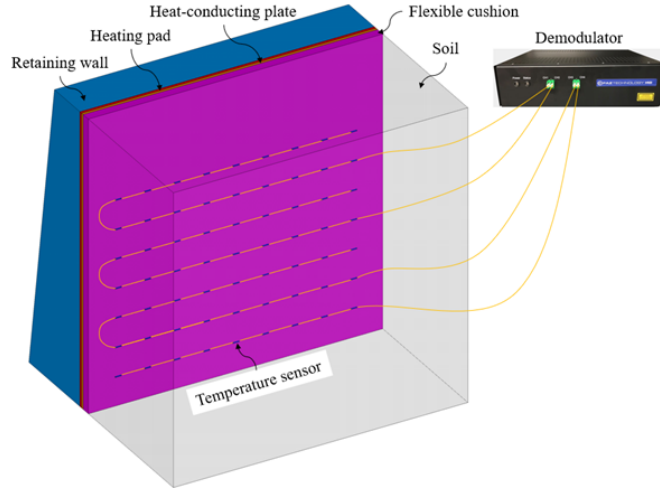


Fig. 2. Monitoring system of earth pressure with surface heat source.

3. Calibration

3.1. Test model

In order to ascertain the relationship between the pressure exerted on the flexible cushion and the temperature variation on its top surface, a calibration test was conducted following the test scheme illustrated in Fig. 3. Firstly, a concrete plate with dimensions of 40 cm $\times$ 40 cm $\times$ 10 cm was placed at the bottom to simulate a soil-retaining structure. Subsequently, a 3 mm-thick silicone heating pad was placed on the concrete plate as the surface heat source. To ensure the uniform distribution of heat released by the silicone heating pad, a 3 mm-thick aluminium plate was arranged on top of the heating pad to serve as a heat-conducting plate. Then, the flexible cushion was laid on the heat-conducting plate, and an FBG temperature sensor encapsulated in a copper tube with an outer diameter of 4 mm and a length of 50 mm was affixed to the top surface of the flexible cushion to monitor the temperature variation. Finally, river sand was poured on the flexible cushion and tamped. The aforementioned test model was placed in the centre of a rigid self-balancing reaction frame. Subsequently, a steel plate with a side length of 20 cm and a thickness of 12 mm was placed on the surface of the river sand to serve as a rigid pressure plate. A screw jack was employed to apply the pressure load, and the load was measured by a force transducer set at the front of the jack piston. To prevent lateral collapse of the soil during the loading process, a closed square plastic frame was adopted for confinement.

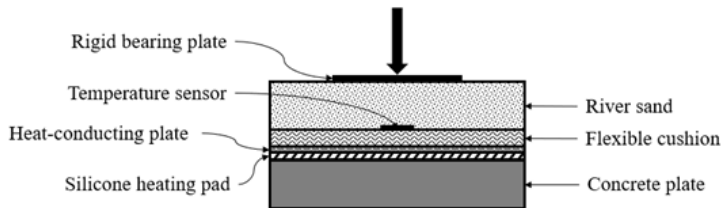


Fig. 3. Schematic diagram of the loading scheme for the calibration test.

3.2. Materials and procedures

Polyurethane sponge pad and silicone foam board with the planar size of 40 cm × 40 cm were separately used as the flexible cushion, and calibration tests were conducted on three specimens for each material. The thermal and mechanical properties of the material were shown in Table 1. Three specimens of polyurethane sponge pads, namely JAZ-1, JAZ-2, and JAZ-3, were all 30 mm thick to verify the accuracy of the measurement results. To investigate the influence of flexible cushion thickness on the measurement results, silicone foam board specimens were fabricated with thicknesses of 20 mm, 25 mm, and 30 mm, respectively. These specimens were designated as GJ-1, GJ-2, and GJ-3.

During the entire heating and cooling process, the wavelength variation of the measuring point located at the centre of the flexible cushion top surface was monitored in real time by an FBG demodulator, with a sampling frequency of 1 Hz. The measurement process was as follows: initially, a predetermined load was applied through the jack. Subsequently, the FBG demodulator was activated to initiate the test after a 1.5 hour stabilization period of the pressure. Then, an ambient temperature test was conducted for 60 seconds under the unheated state, and then started the heating by applying the heating pad. After 180 seconds, the heating pad was turned off, allowing it to cool naturally.

Table 1. Thermal and mechanical properties of the flexible cushion.

Type of flexible cushion	Density [kg/m ³]	Elastic modulus [MPa]	Thermal conductivity [W/(m·K)]
Polyurethane sponge pad	83.1	0.09	0.04
Silicone foam board	681.5	1.22	0.16

3.3. Calibration results

The wavelength is converted to temperature according to the temperature sensitivity coefficient of the FBG temperature sensor. The temperature rise (ΔT) *time-history* (TH) curve of the middle of the top surface of the polyurethane sponge pad specimen JAZ-1 under different load conditions is shown in Fig. 4 (the specimens JAZ-2 and JAZ-3 are similar to it). It can be seen that: firstly, a clear correlation exists between the TH curves of temperature rise and pressure (p), with higher pressures resulting in faster temperature rises. Secondly, the low thermal conductivity and thickness of polyurethane sponge pads lead to a limited temperature amplitude. Consequently, a measurement system with high temperature measurement sensitivity should be adopted. Thirdly, under different pressure conditions, the TH curve exhibits linear characteristics over a specific time period. The initiation of the linear temperature rise stage advances with increasing pressure, and this linear temperature rise stage has a duration of approximately 100 seconds.

The TH curve of ΔT in the middle of the top surface of the silicone foam specimen GJ-2 under different loads is illustrated in Fig. 5 (specimens GJ-1 and GJ-3 are similar to it). Moreover, these curves exhibited characteristics essentially consistent with those presented in Fig. 4. As evident from Fig. 5, the TH curves for 0 kPa and 23.61 kPa pressures are largely coincident. This is attributed to the fact that silicone foam has higher hardness than the polyurethane sponge pad. When subjected to low pressure, the compression deformation of silicone foam is correspondingly negligible, thereby resulting in a less pronounced difference in the TH curves. In addition, when a silicone foam board was adopted as the flexible cushion, the duration of the linear heating stage at the centre of the top surface is longer than that of the polyurethane sponge pad, at approximately seconds.

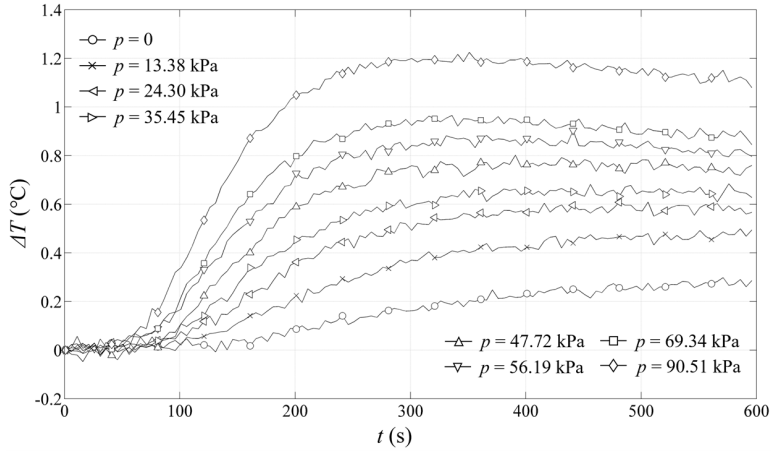


Fig. 4. Time-history curves of temperature rise in the middle of the top surface of polyurethane foam pad specimen JAZ-1.

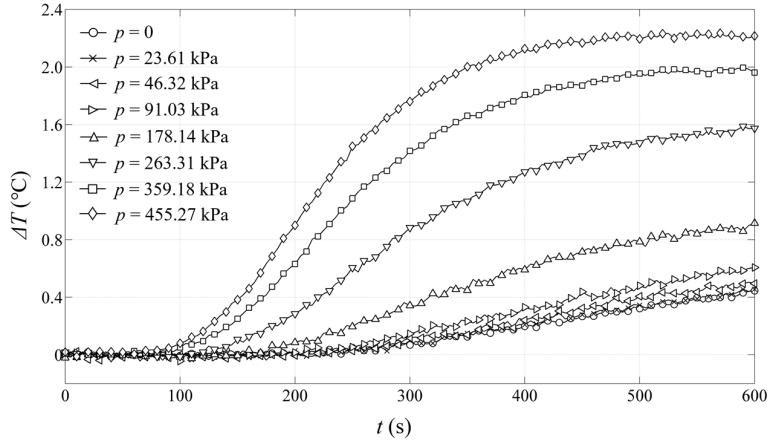


Fig. 5. Time-history curves of the middle of the top surface of silicone foam board specimen GJ-2.

From the analysis above, the slope of the linear heating stage curve at the central measuring point on the top surface of the flexible cushion exhibits a significant correlation with the applied pressure, which can be utilized as a pressure discrimination index. A well-established correlation exists between the initial time and duration of the warming phase, the material properties of the flexible cushion, and the external pressure applied to it. Accordingly, the linear correlation coefficients R at each moment are calculated using:

$$R = \frac{\sum_{i=j}^{j+t_n} (t_i - t') (T_i - T')}{\sqrt{\sum_{i=j}^{j+t_n} (t_i - t')^2 \sum_{i=j}^{j+t_n} (T_i - T')^2}}, \quad (3)$$

where t and ΔT are time and temperature rise, respectively; t' and $\Delta T'$ are the average values of time and temperature rise during the fitted time period taken, respectively. This calculation is performed by taking the length of the linear fitting time period as t_n .

The time period corresponding to the maximum value of the linear correlation coefficient is identified as the optimal time period. The slope k_v of the linear fit in this time period is designated as the initial temperature rise rate. This is then calibrated against the pressure p . The calibration results of the three polyurethane sponge pads are presented in Fig. 6. The three specimen tests demonstrate significant repeatability, and k_v and p are found to be in an approximately linear relationship. The overall correlation coefficient of the three specimen calibrations is recorded as 0.989, indicating a strong correlation between the variables.

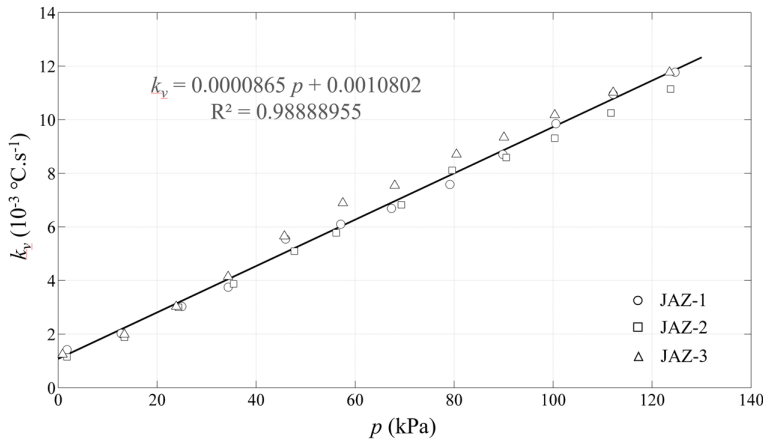


Fig. 6. Calibration relationship between k_v and p established with polyurethane foam as a flexible cushion.

The calibration results of the three silicone foam boards are displayed in Fig. 7. As indicated in Fig. 7, for thicknesses of 25 mm and 30 mm, the calibration relationship between k_v and p is characterized by linearity. The pressure corresponding to the intersection of the two fitted lines is referred to as the critical pressure. For silicone foam boards with a thickness of 25 mm, the critical pressure is approximately 130 kPa. Meanwhile, for those with a thickness of 30 mm, it is approximately 180 kPa. It is evident that as the pressure exceeds the critical pressure, the sensitivity coefficient undergoes a substantial increase. Furthermore, the thickness of the silicone foam board directly impacts the sensitivity, with greater thickness corresponding to reduced sensitivity. Given that the pore size of the silicone foam board with a thickness of 20 mm is smaller, its porosity is lower, and its hardness is greater than that of the other two thicknesses. Consequently, the calibration relationship between k_v and p established for the silicone foam board with a thickness of 20 mm differs from that of the other two thicknesses, and k_v increases exponentially with p .

For a given 30 mm-thick flexible cushion, the polyurethane sponge pad exhibits a greater sensitivity to pressure than the silicone foam board. This disparity is attributed to the lower hardness of the polyurethane sponge pad relative to the silicone foam board. Furthermore, the compressed thickness of the polyurethane sponge pad is more significant under the same pressure. However, when the pressure exceeds a certain value, the compressed thickness of the softer polyurethane sponge pad will not change significantly, which means the softer polyurethane sponge pad has a small pressure measurement range.

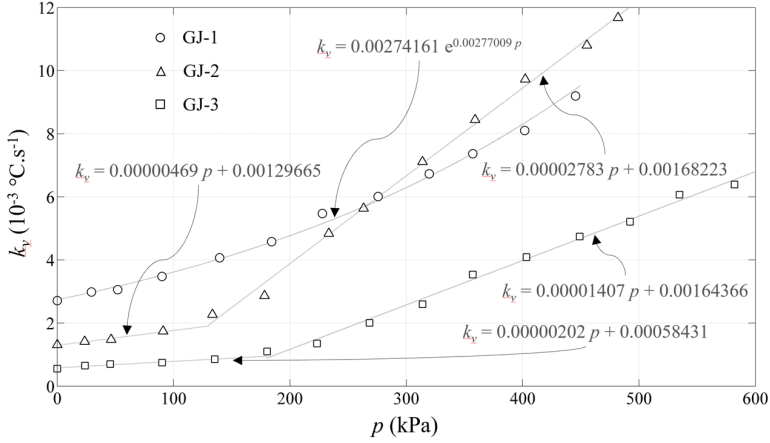


Fig. 7. Calibration relationship between k_v and p established by using a silica gel foam sheet as a flexible cushion.

To avoid dimensional ambiguity and eliminate the influence of heating power on the pressure identification results, the k_v when the pressure is 0 is designated as a benchmark, and the k_v under other pressure states is compared with it to obtain the dimensionless quantity κ , as expressed in the following:

$$\kappa = \frac{k_v(d_t)}{k_{v0}}, \quad (4)$$

where $k_v(d_t)$ is the value of k_v at the compressive deformation d_t , and k_{v0} is the value of k_v at $d_t = 0$ (zero pressure). The compressive deformation d_t is related to the applied pressure state and mechanical properties of the flexible cushion. Based on the calculation principle of foundation settlement, the compressive deformation of the flexible cushion can be calculated by the following equation [26]:

$$d_t = \int_0^{t_0} \frac{p(z)}{E_s} dz, \quad (5)$$

where $p(z)$ is the pressure on the thickness direction of the flexible cushion and E_s is the deformation modulus of the flexible cushion.

The relationship between κ and p of the two flexible cushions is illustrated in Fig. 8 and Fig. 9, respectively. It is evident from Fig. 9 that, under pressures below 130 kPa, the κ - p relationship established using three thicknesses of silicone foam board demonstrates a high degree of correlation. However, when the pressure exceeds 180 kPa, the increase rate of κ with p is proportional to the thickness of the silicone foam board.

4. Validation

In order to verify the validity of the proposed surface heat source method for earth pressure monitoring, temperature response tests under various loading cases were carried out on a 30 mm thick polyurethane sponge pad. The relationship between the pressure and the dimensionless quantity κ established by the calibration test (Fig. 8) was used to invert the distribution of the earth pressure. The inverted earth pressure was compared with that calculated based on the actual loading amount.

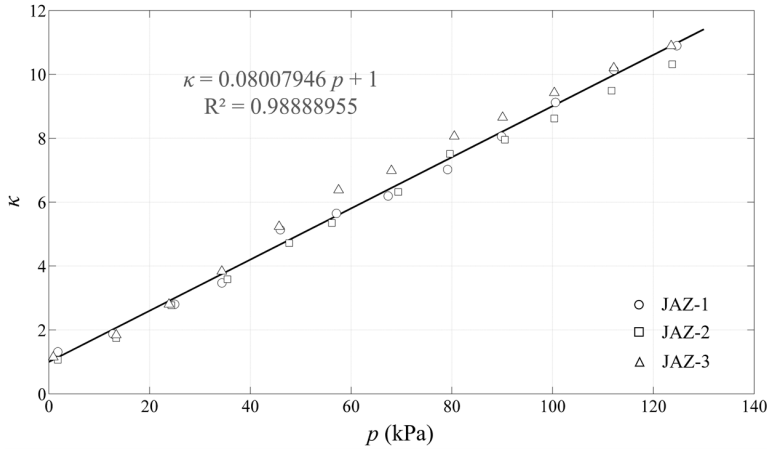


Fig. 8. Established relationship between κ and p with polyurethane sponge as a flexible cushion.

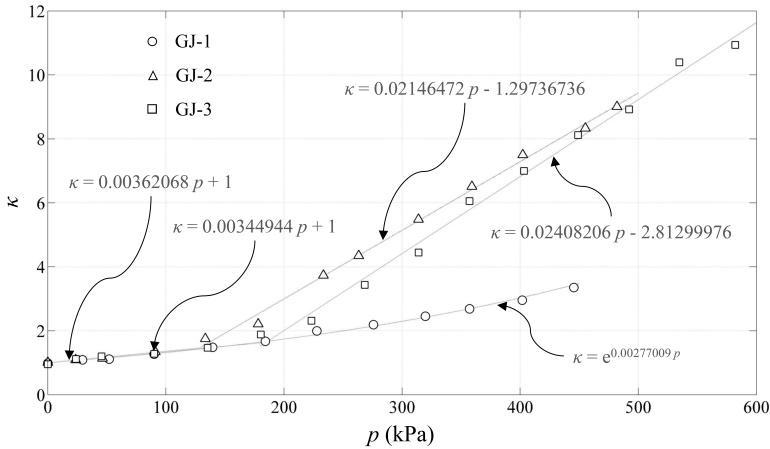


Fig. 9. Established relationship between κ and p with silica gel foam as a flexible cushion.

4.1. Test model and experimental setup

The monitoring system consists of a surface heat source, a heat conduction plate, a flexible cushion, and a temperature sensing system. A fence composed of stainless steel plate with a thickness of 3 mm was installed on the concrete floor, with internal dimensions of 800 mm × 600 mm × 200 mm. Inside the fence, a heating pad (3 mm thick, with a planar size of 700 mm × 500 mm), a heat-conducting aluminium plate (3 mm thick, with a planar size of 700 mm × 500 mm), and a polyurethane foam pad with a hardness of 85D (30 mm thick, with a planar size of 790 mm × 590 mm) were sequentially bonded using thermally conductive adhesive. Then, 12 FBG temperature sensors were arranged on the top surface of the polyurethane foam pad using thermally conductive adhesive, as shown in Fig. 10. The positioning, numbering of the temperature sensors and the loading region are presented in Fig. 11. Finally, wet sand was uniformly poured into the fence and tamped, forming a covering layer with a thickness of 60 mm.

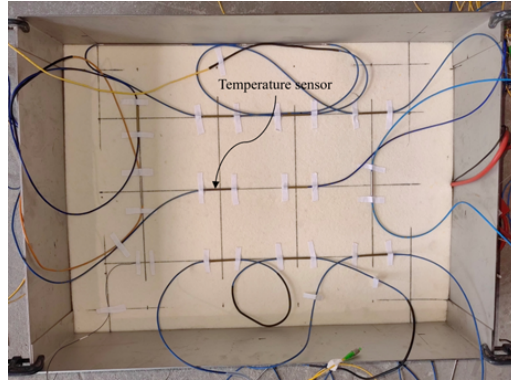


Fig. 10. Layout of the temperature sensors.

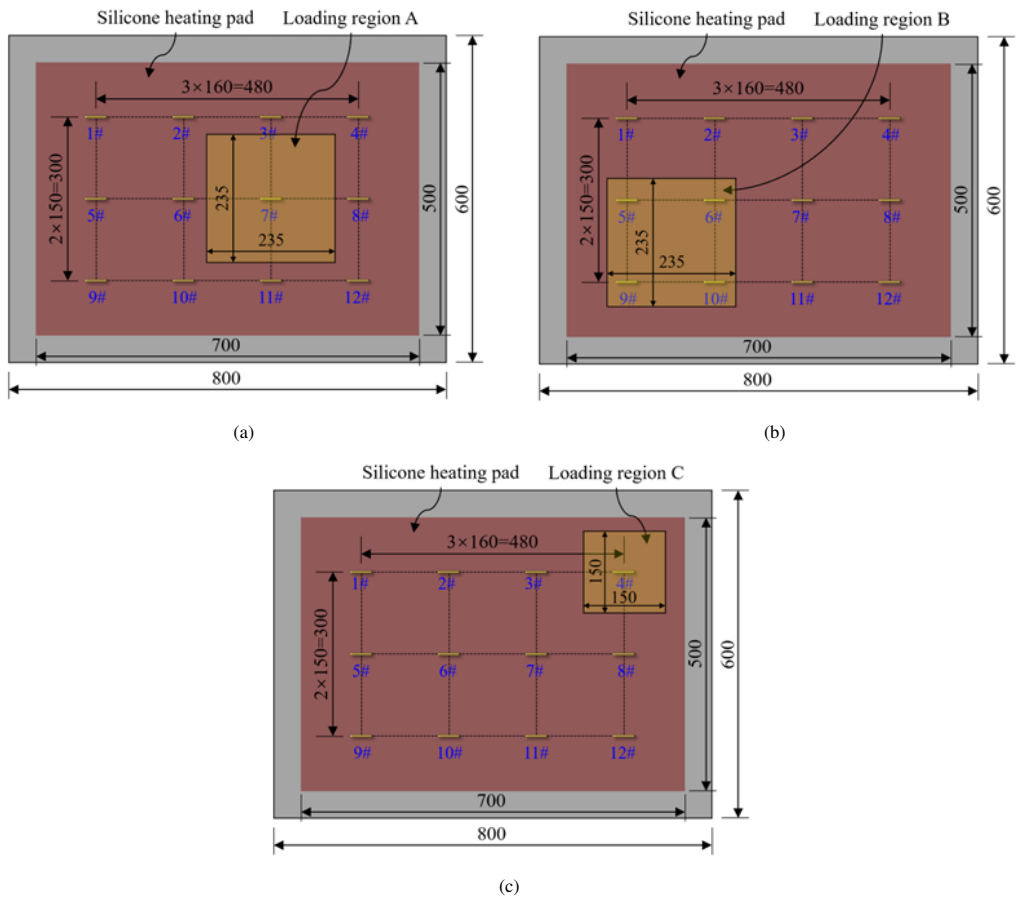


Fig. 11. Position, number, and loading area of the temperature sensors: a) loading region A, b) loading region B, and c) loading region C.

4.2. Experimental Procedure

The test steps were as follows:

- 1) Connecting the connector of the FBG temperature sensor line with the FBG demodulator, and setting the temperature of the silicone heating pad to 60 °C with the digital temperature controller.
- 2) Carrying out the temperature response test of each measurement point on the top surface of the flexible cushion in the unloaded state as a benchmark. Initially, the test is performed at ambient temperature for 60 seconds, repeated after the cushion is heated at 60 °C by the heating pad for 180 seconds, and at last, performed again during the natural cooling process. Through the whole process of heating and cooling, the wavelength changes of the measurement point on the top surface of the flexible flat surface are recorded by the FBG demodulator with real time monitoring.
- 3) Loading in the predetermined loading position by the means of the steel plate stacking when the measurement points regain the ambient temperature, as shown in Fig. 12.
- 4) After stabilizing the loading for 1.5 h, the temperature response test is carried out according to Step 2 above).

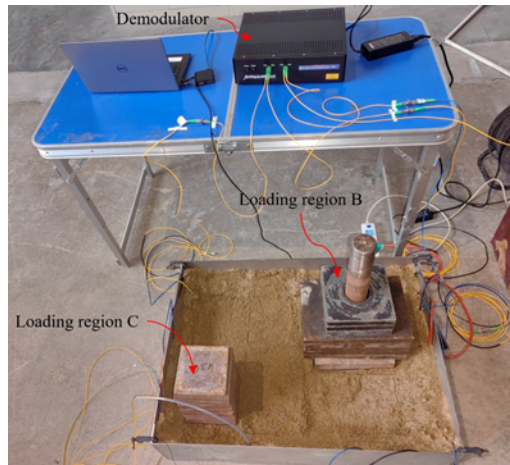


Fig. 12. Photographs of the test site.

4.3. Test Cases

A total of nine cases were tested, as shown in Table 2.

4.4. Test results

Based on the temperature response curve of each measurement point, k_v was calculated. The k_v of each measurement point in Case 1 (no load condition) was taken as the reference, and the k_v of each measurement point in other cases was converted to the dimensionless quantity κ . The fitting relationship between κ and p established in the calibration test (Fig. 8) was then utilized to invert the pressure p at each measurement point. To visualize the pressure distribution characteristics of each case, the pressure at the peripheral boundaries of the model was set to 0.

Table 2. Testing cases.

Case	Loading region	Loading weight [kg]
1	None	0
2	A	72.1
3	A	120.5
4	A	187.4
5	B	53.5
6	B	120.5
7	B	187.4
8	C	35.0
	B	117.1
9	C	50.4
	B	72.1

Then, the interpolation operation was carried out by incorporating the inverted pressure values at the 12 internal measurement points. Finally, the pressure distributions of each case were plotted as shown in Fig. 13.

It can be seen that:

- 1) the inverted pressure of the measuring point located in the loading area is obviously higher than that of the other measuring points. The characteristics of the earth pressure distribution of each case are consistent with the actual loading.
- 2) The inverted pressure of the measuring point outside the loading area is not zero, which is due to both the measurement error and the pressure diffusion.
- 3) In Cases 3 and 6, the applied load is identical, with the only difference being the loading position. However, the loading range in the earth pressure distribution of Case 6 is significantly larger than in Case 3. A similar phenomenon is also observed in Case 4 and Case 7. This discrepancy can be attributed to the fact that there are four measurement points in the loading area of Case 6 and Case 7, while there is only one measurement point in the loading area of Case 3 and Case 4. This results in the distortion of the pressure distribution range of the region due to the small number of measurement points in the interpolation operation.
- 4) The earth pressure distribution of Case 5 also has relatively high earth pressure values near the Measurement Point 7. It is due to the shorter time interval between the tests of Case 4 and Case 5, and the compressive deformation near the Measurement Point 7 is not been fully recovered after the unloading of Case 4.

A comparison of inverted pressure of each measuring point in the loading area of each case and the pressure calculated according to the actual loading amount is presented in Table 3. As can be seen, the two sets of pressure values show high consistency. However, for some individual measuring points, slightly larger errors might occur due to deviations in the loading area or incomplete recovery of deformation caused by loading in the previous working condition. The root mean square error of the inverted pressure for all measurement points under each case is calculated to be 1.75 kPa.

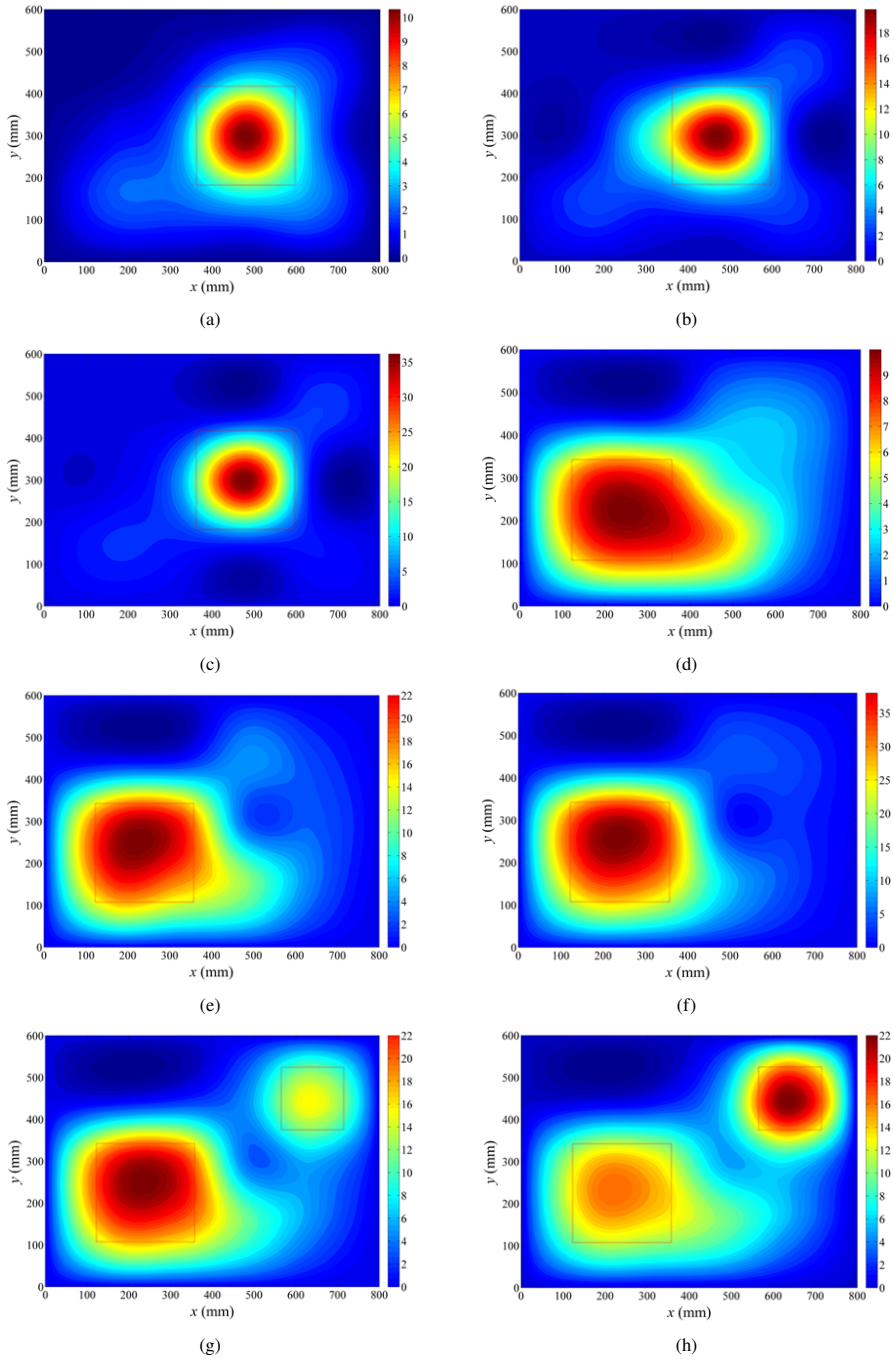


Fig. 13. Contours of earth pressure distribution for each case [kPa]: a) Case 2, b) Case 3, c) Case 4, d) Case 5, e) Case 6, f) Case 7, g) Case 8, and h) Case 9.

Table 3. Comparison of inverted pressure and actual pressure in the loading area.

Case	Measurement point	Load [kg]	Inverted pressure [kPa]	Actual pressure [kPa]	Error [%]
2	7	72.1	10.5	12.8	-18.0
3	7	120.5	20.2	21.4	-5.6
4	7	187.4	36.0	33.3	8.1
5	5	53.5	8.2	9.5	-13.7
	6		8.3		-12.6
	9		8.0		-15.8
	10		8.9		-6.3
6	5	120.5	21.9	21.4	2.3
	6		21.6		0.9
	9		20.1		-6.1
	10		17.7		-17.3
7	5	187.4	36.3	33.3	9.0
	6		36.1		8.4
	9		31.5		-5.4
	10		30.4		-8.7
8	4	35.0	15.9	15.3	3.9
	5	117.1	23.0	20.8	10.6
	6		22.3		7.2
	9		20.5		-1.4
	10		20.3		-2.4
9	4	50.4	22.4	22.0	1.8
	5	72.1	14.0	12.8	9.4
	6		14.5		13.3
	9		13.5		5.5
	10		13.3		3.9

5. Discussion

To further clarify the influencing factors of sensor sensitivity, the effects of ambient temperature, mechanical properties of the flexible cushion, and thermodynamic properties of soil on sensor sensitivity were discussed in detail in this section.

5.1. Effects of ambient temperature on the measurement result

During the measurement process of this study, ambient temperature testing was conducted only for 60 seconds before heating. Since the duration of the testing was relatively short, the influence of time-varying ambient temperature is negligible, and thus the variation of ambient temperature is not considered in the analysis. However, in long-term monitoring scenarios,

significant temperature fluctuations occur across different seasons, which may affect the changes of material thermodynamic parameters and further influence the heating rate. Therefore, it is recommended that calibration models be established under different ambient temperature conditions to eliminate such interference and improve the applicability of the proposed method in long-term engineering monitoring.

5.2. Effects of mechanical properties of the flexible cushion on the measurement result

Sensor sensitivity is a critical index for evaluating sensor performance. For the earth pressure monitoring system proposed in this paper, as shown in Fig. 4, the higher the slope of the calibration curve between k_v and p , the higher the sensitivity. The sensitivity of the proposed monitoring system is mainly determined by the thickness as well as thermal and mechanical properties of the flexible cushion. It is found that smaller elastic modulus of the flexible cushion leads to higher sensitivity to earth pressure variations, but with a limited measurement range. When the applied pressure is sufficiently high, the thickness of the flexible cushion can hardly change. Therefore, flexible cushions with a low elastic modulus are recommended under low earth pressure conditions where high measurement sensitivity is required. In contrast, flexible cushions with a high elastic modulus should be adopted under high earth pressure to ensure a large measurement range. To achieve a good balance between sensitivity and measurement range, a composite cushion can be fabricated by stacking the polyurethane sponge pad and silicone foam board. During testing, the cushion with a low elastic modulus deforms dominantly at the initial low-pressure stage to enhance sensitivity, while the flexible cushion with a high elastic modulus undergoes the main deformation under high-pressure conditions.

5.3. Effects of thermodynamic parameters of the soil on the measurement result

In practical engineering, the density, specific heat, and thermal conductivity of soil vary with its gradation and compactness, which will affect the heat transfer mechanism. Therefore, in this section, the influence of soil thermodynamic parameters on the measurement results is studied by numerical simulation. When the soil thermal conductivity k_t is set to 0.6, 0.7 and 0.8 $\text{W}\cdot\text{m}^{-1}\cdot^\circ\text{C}^{-1}$, respectively, the temperature TH curves at the centroid of the flexible cushion outer surface are shown in Fig. 14. It can be seen that the thermal conductivity of soil has no obvious effect on the early-stage heating rate of the outer surface of the flexible cushion, but has a significant influence on its later-stage heating rate. The fitting slopes of the TH curves for the three cases during the period from 120 s to 250 s are 0.00209918 $^\circ\text{C}\cdot\text{s}^{-1}$, 0.00205383 $^\circ\text{C}\cdot\text{s}^{-1}$, and 0.00201043 $^\circ\text{C}\cdot\text{s}^{-1}$, respectively. With an increase in the thermal conductivity of the soil, the heating rate of the outer surface of the flexible cushion gradually decreases.

When the thermal conductivity of the soil is different, the fitting relationship between k_v and the compression thickness of the d_t is shown in Fig. 15. It can be observed that as the thermal conductivity of the soil increases, the slope ξ of the fitting straight line between k_v and d_t decreases gradually, but the variation amplitude is small. This indicates that the sensitivity of the soil pressure measurement system decreases with the increase in thermal conductivity of the soil. Due to the non-uniformity of the soil, its thermal conductivity exhibits significant discreteness. In practical applications, since it is impossible to ensure uniform thermal conductivity across all regions of the soil, it is not suitable to use k_v as the discriminant index for earth pressure.

If the dimensionless quantity κ defined by (4) is adopted as the discriminant index, the fitting relationship between κ and d_t under different soil thermal conductivities is as shown in Fig. 16. It can be seen that, with the increase in thermal conductivity of the soil, the fitting straight lines

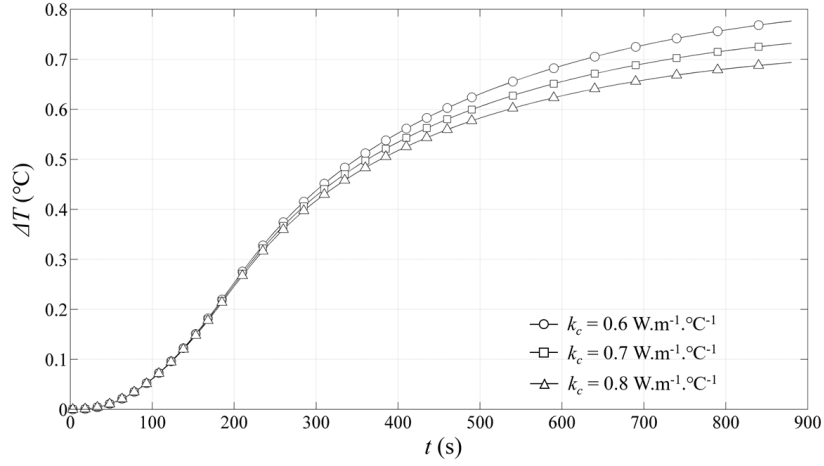


Fig. 14. Effect of soil thermal conductivity on the temperature response of the outer surface of the flexible cushion.

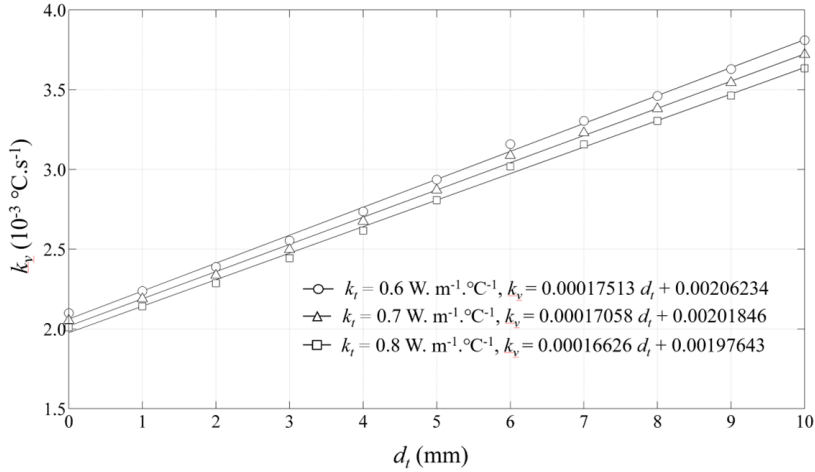


Fig. 15. Calibration relationship between k_v and d_t for different k_t .

between κ and d_t basically coincide. Although the slope of the fitting lines shows a decreasing trend with the increase in thermal conductivity of the soil, the variation amplitude is very small. Therefore, using the dimensionless quantity κ as the discriminant index can eliminate the error caused by the uncertainty of thermal conductivity of the soil.

When the soil density ρ_t is set to $1800 \text{ kg}\cdot\text{m}^{-3}$, $1900 \text{ kg}\cdot\text{m}^{-3}$ and $2000 \text{ kg}\cdot\text{m}^{-3}$ respectively, the time-history curves of temperature at the centroid of the outer surface of the flexible cushion are as shown in Fig. 17. The results show that the influence of soil density on the later-stage heating rate of the outer surface of the flexible cushion is more significant than that on the early-stage heating rate. The fitting slopes of the time-history curves for the three cases during the period from 120 s to 250 s are $0.00219625 \text{ }^\circ\text{C}\cdot\text{s}^{-1}$, $0.00209918 \text{ }^\circ\text{C}\cdot\text{s}^{-1}$ and $0.00201026 \text{ }^\circ\text{C}\cdot\text{s}^{-1}$, respectively. The influence of soil density on the early-stage heating rate of the outer surface of the flexible cushion is stronger than that of thermal conductivity of the soil. With the increase in soil density, the heating rate of the outer surface of the flexible cushion decreases gradually.

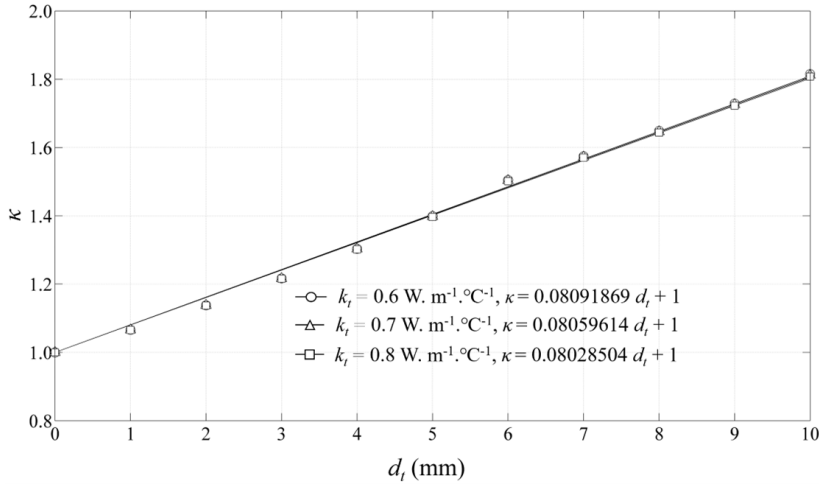


Fig. 16. Calibration relationship between k_v and d_t for different k_t .

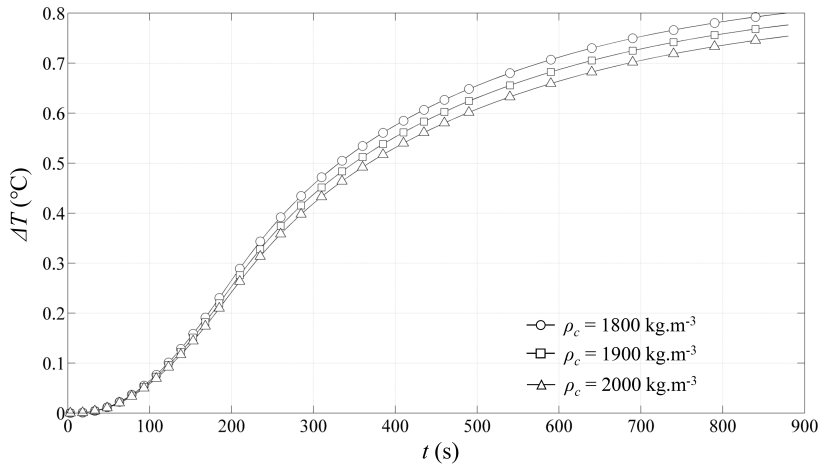


Fig. 17. Effect of soil density on the temperature response of the outer surface of the flexible cushion.

When the soil density varies, the fitting relationship between k_v and d_t is shown in Fig. 18. It can be seen that, as the soil density increases, the slope ξ of the fitting line between k_v and d_t decreases gradually, but the variation is small. This demonstrates that the sensitivity of the soil pressure measurement system decreases with increasing soil density. Similarly, using the dimensionless quantity κ defined by (4) as the discriminant index can eliminate the error caused by the uncertainty of soil density.

In the heat conduction differential equations, density and specific heat have similar effects on heat transfer regularity. Therefore, in this earth pressure measurement system, when the dimensionless quantity κ defined by (4) is used as the discriminant index, the influence of soil specific heat on the fitting relationship between k_v and d_t is the same as that of soil density.

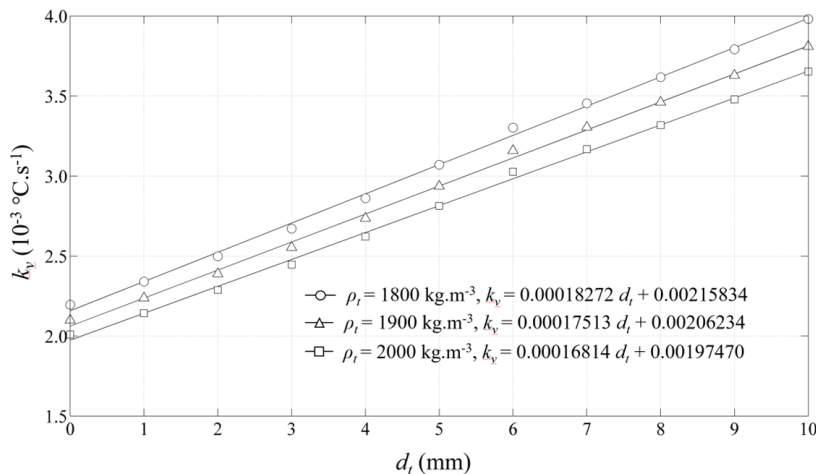


Fig. 18. Calibration relationship between k_v and d_t for different ρ_t .

6. Conclusions

The compression deformation of the flexible cushion leads to the reduction of thermal conductivity. In this study, a self-sensing intelligent retaining structure for measuring earth pressure was proposed by using this thermal property. The structure is instrumented with an FBG temperature sensor array on the exterior surface of the flexible cushion to form a sensing array. The proposed scheme enables large-scale and quasi-distributed measurements of earth pressure which will not affect the in-situ stress state of the soil or change the distribution of earth pressure. The calibration and validation tests of the earth pressure measurement were carried out using this structure, respectively. The conclusions of this research can be summarized as follows:

- 1) The heating pattern of the outer surface of the flexible cushion is found to be related to the pressure it is subjected to, and the slope of the linear section of the heating curve can be used as a pressure discrimination index.
- 2) The calibrations obtained by using a polyurethane sponge pad of the same thickness as the flexible cushion are basically in agreement, indicating good repeatability of the method.
- 3) The thickness of the flexible cushion exerts a substantial influence on the sensitivity of the earth pressure measurement, with thicker plates exhibiting reduced sensitivity.
- 4) The measurable range of earth pressure is contingent on the mechanical properties of the flexible cushion. For a given thickness, the harder the material, the broader the range.
- 5) In the validation test, the distribution of inverted pressure using the calibration relationship is largely consistent with the actual loading situation, and the root mean square error of the inverted pressure and the actual pressure is 1.75 kPa.

Acknowledgements

This work is supported by the Natural Science Foundation of Sichuan Province (No. 2025ZNSFSC0306). The authors sincerely thank Dr. Ting Ai of the Structural Laboratory of Civil Engineering of Sichuan University for her valuable assistance during the test.

References

- [1] Zhang, C., Zhu, H., Shi, B., & She, J. (2014). Interfacial characterization of soil-embedded optical fiber for ground deformation measurement. *Smart Materials and Structures*, 23(9), 095022. <https://doi.org/10.1088/0964-1726/23/9/095022>
- [2] Zhou, Y., & Wei, H. (2024). Review on the research progress of earth pressure on slope retaining structure. *Frontiers in Earth Science*, 12, 1468607. <https://doi.org/10.3389/feart.2024.1468607>
- [3] Wachman, G. S., & Labuz, J. F. (2011). Soil-structure interaction of an earth pressure cell. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(9), 843–845. [https://doi.org/10.1061/\(asce\)gt.1943-5606.0000501](https://doi.org/10.1061/(asce)gt.1943-5606.0000501)
- [4] Weiler, W. A., & Kulhawy, F. H. (1982). Factors affecting stress cell measurements in soil. *Journal of the Geotechnical Engineering Division*, 108(12), 1529–1548. <https://doi.org/10.1061/ajgeb6.0001393>
- [5] Jayalath, C. P. G., & Wimalasena, K. D. (2021). Laboratory calibration of earth pressure cells. *International Journal of Geomate*, 20(82), 61–67. <https://doi.org/10.21660/2021.82.Gx362>
- [6] Bishnoi, D., Patil, V., & Dasaka, S. M. (2024). Calibration of boundary-type earth pressure cells with sand. *Geotechnical Testing Journal*, 47(4), 863–878. <https://doi.org/10.1520/gtj20220231>
- [7] Bishnoi, D., Dasaka, S., & Patil, V. S. (2023). Measurement variability of calibration factor of earth pressure cells with different contact materials. *Measurement*, 224, 113934. <https://doi.org/10.1016/j.measurement.2023.113934>
- [8] Li, M., Zhu, L., Shu, J., Lu, Z., & Liu, Y. (2024). Study on calibration tests for interface-type earth pressure cell based on matching error analysis. *Sensors*, 24(23), 7778. <https://doi.org/10.3390/s24237778>
- [9] Kisała, P. (2022). Physical foundations determining spectral characteristics measured in Bragg gratings subjected to bending. *Metrology and Measurement Systems*, 29(3), 573–584. <https://doi.org/10.24425/mms.2022.142275>
- [10] Cieszyzyk, S., Kisała, P., Skorupski, K., Panas, P., & Klimek, J. (2018). Rotation and twist measurement using tilted fibre Bragg gratings. *Metrology and Measurement Systems*, 25(3), 429–440. <https://doi.org/10.24425/123893>
- [11] Luo, Z., Hua, P., Xu, B., Zhang, X., Shi, Y., & Dong, H. (2023). Research on small-sized earth pressure sensor based on ultra-weak fiber Bragg grating. *Optik*, 280, 170780. <https://doi.org/10.1016/j.ijleo.2023.170780>
- [12] He, F., Chen, J., Li, C., & Xiong, F. (2022). Temperature tracer method in structural health monitoring: A review. *Measurement*, 200, 111608. <https://doi.org/10.1016/j.measurement.2022.111608>
- [13] Cao, D., Shi, B., Wei, G., Chen, S., & Zhu, H. (2018). An improved distributed sensing method for monitoring soil moisture profile using heated carbon fibers. *Measurement*, 123, 175–184. <https://doi.org/10.1016/j.measurement.2018.03.052>
- [14] Zheng, C., Wu, Z., Qian, J., & Zhang, Y. (2023). Applicability of optical fibers for monitoring the temperature and moisture of freeze-thaw soil. *Journal of Testing and Evaluation*, 51(5), 2801–2816. <https://doi.org/10.1520/jte20210779>
- [15] Chen, J., Xiong, F., Zheng, J., Ge, Q., & Cheng, F. (2019). The influence of infiltration angle on the identification effect of seepage with linear heat source method. *Measurement*, 148, 106974. <https://doi.org/10.1016/j.measurement.2019.106974>
- [16] Liu, R., Chen, L., Yan, S., Luo, H., Tian, F., & Xie, Z. (2024). Seepage monitoring at variable spatial positions under natural convection with active heating. *Flow Measurement and Instrumentation*, 101, 102759. <https://doi.org/10.1016/j.flowmeasinst.2024.102759>

- [17] Cheng, F., Chen, J., & Wei, X. (2025). Thermal tracing method for surface spalling monitoring in underwater concrete structures. *Construction and Building Materials*, 489, 142445. <https://doi.org/10.1016/j.conbuildmat.2025.142445>
- [18] Zhang, C., Chen, J., Li, W., Xiong, F., & Deng, X. (2024). Optimization scheme of water irrigation and electric heating method for multi-crack detection in wading-concrete structures. *Measurement*, 228, 114353. <https://doi.org/10.1016/j.measurement.2024.114353>
- [19] Chen, J., Xiong, F., Zhu, Y., & Yan, H. (2020). A crack detection method for underwater concrete structures using sensing-heating system with porous casing. *Measurement*, 168, 108332. <https://doi.org/10.1016/j.measurement.2020.108332>
- [20] Chen, J., Wei, X., & Luo, Y. (2026). Precise crack localization in underwater concrete structures via active thermal tracing and optical fiber sensing. *Sensor Review*, 1–12. <https://doi.org/10.1108/sr-09-2025-0742>
- [21] Chen, J., Wei, X., & Qiao, F. (2026). Scour monitoring of underwater foundations using abrupt changes in cooling rate. *Journal of Civil Structural Health Monitoring*, 16(1), 5. <https://doi.org/10.1007/s13349-025-01041-6>
- [22] Hatley, R., Shehata, M., Sayde, C., & Castro-Bolinaga, C. (2023). High-resolution monitoring of SCOUR using a novel fiber-optic distributed temperature sensing device: a proof-of-concept laboratory study. *Sensors*, 23(7), 3758. <https://doi.org/10.3390/s23073758>
- [23] Liu, Y., Xiao, H., Huang, S., Wu, W., & Chen, Z. (2018). Research on the layout of optical fibers applied for determining the integrity of cast-in-situ piles. *Optical Fiber Technology*, 45, 173–181. <https://doi.org/10.1016/j.yofte.2018.07.008>
- [24] Fan, K., Zou, W., Zhang, P., Wang, X., & Shen, Y. (2023). Laboratory investigation and theoretical analysis of lateral pressure exerted by expansive soils on retaining walls with expanded polystyrene geofoam block upon water infiltration. *Geotextiles and Geomembranes*, 52(3), 332–341. <https://doi.org/10.1016/j.geotexmem.2023.11.005>
- [25] Zou, W., Xiang, Q., Pei, Q., Han, Z., Zhuang, Y., Lin, Y., Zhang, H., Dai, Z., & Zhang, H. (2025). Reducing lateral earth pressure of expansive soils on retaining walls using EPS geofoam inclusions: Field study and estimation approaches. *Computers and Geotechnics*, 188, 107533. <https://doi.org/10.1016/j.compgeo.2025.107533>
- [26] Guang-Hua, Y. (2021). Innovation and development of modern theories for foundation design. *Chinese Journal of Geotechnical Engineering*, 43(1), 1-18. <https://doi.org/10.11779/cjge202101001>



Lin Zhao received her B.Sc. degree from Xihua University in 2022 and her M.Sc. degree from Guangxi University of Science and Technology in 2025. She is currently pursuing her Ph.D. degree at Sichuan University. Her main research interests include structural health monitoring.

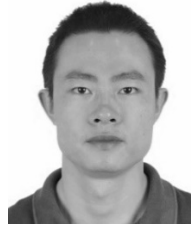


Ling He received his B.Sc. in civil engineering and his first Master's degree in Structural Engineering from Chongqing University, China in 2007 and 2010 respectively, and achieved his second Master's degree in Civil Engineering from the University of Canterbury (New Zealand). From 2010 to 2021, he was a senior structural engineer employed by several engineering consulting companies in China. From 2022 to now, he has resettled in New Zealand and continued his engineering career. As a member of Engineering New Zealand (Te Ao Rangahau), he specializes in seismic assessments, structural repairs, and comprehensive designs.

Rangahau), he specializes in seismic assessments, structural repairs, and comprehensive designs.



Zhengyi Zeng received the B.Sc. degree from Jilin University in 2025. He is currently working toward his M.Sc. degree at Sichuan University. His research interests focus on structural health monitoring.



Jiang Chen received his B.Sc. degree in civil engineering and his Ph.D. degree in geotechnical engineering from Sichuan University, Chengdu, China, in 2004 and 2009, respectively. From 2009 to 2012, he was a senior engineer with the Scientific Research Institute, HydroChina Kunming Engineering Corporation, Kunming, China. Since 2012, he has been an associate professor with the Department of Civil Engineering, Sichuan University, Chengdu, China.

He is the author of more than 100 articles. His research interests include safety monitoring in civil engineering, applications of optical fiber sensing technology in civil engineering, earthquake resistance analysis of engineering structures, and prefabricated concrete structure.