MATEC Web of Conferences **232**, 04018 (2018) https://doi.org/10.1051/matecconf/201823204018
EITCE 2018

Development of a smart axial strain sensor for static load testing of foundation piles

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Abstract. Sensors of stress or strain currently used in geotechnical and civil engineering applications have the disadvantage that a large quantity of measuring points would result in large bundles of cables. Based on the principle of resistive strain gauge, a type of smart sensor that supports serial communication over RS-485 is developed for the measurement of strain or stress of foundation piles, which has the benefit of good noise tolerance. All the sensors installed along a pile could share a common cable for power supply and communication, and there is no actual limits to pile length. The installation in the field is simple, convenient and efficient. The sensor has a compact structure with reliable waterproof protection. The internal measurement circuit mainly consists of a Wheatstone bridge excitation module, a signal conditioning module, a microcontroller with ADC, a precision voltage reference, and a RS-485 communication module. A group of sensors were calibrated after being assembled, and the calibration results obtained have shown their functionality and reliability.

1 Introduction

Among all the assessment testing methods of deep foundations used in geotechnical investigation, the static load testing is an in situ testing method widely used to evaluate the quality and bearing capacity of foundation piles. During the test, the pile is in a state similar to the working state after the superstructure has been constructed. Axial strain or stress measurement is necessary for the research on the bearing characteristics of the pile segments in different soil layers, and the corresponding side resistance of the pile could also be obtained using axial forces of pile.

Vibrating wire strain gauges have been used in geotechnical and civil engineering applications[1-3]. The vibrating wire strain gauge consists of a vibrating, tensioned wire, and a plucking and pickup coil. The strain is calculated by measuring the resonant frequency of the wire (an increase in tension increases the resonant frequency). Fiber optic sensors are another choice for strain measurement[4-6], but the cost of measurement equipment can be prohibitive.

Currently widely used sensors of stress or strain have some disadvantages. For example, a large quantity of measuring points of stress or strain could result in large bundles of cables, and thus make the installation and the data acquisition more difficult and less efficient, or even damage the integrity of the pile[7].

The proposed axial smart strain sensor features simple structure, easy installation and convenience for testing. The assembled sensor has only one cable for both the communication and the power supply, therefore it is more convenient to attach the sensors to the reinforcement cage of a bored pile in the field.

In this paper, the principle, structure and hardware of the smart axial strain sensor with good noise tolerance are introduced. The sensor consists of a shell, a Wheatstone bridge of four resistive strain gauges, a bridge excitation module, a signal conditioning module, a precision voltage reference, a microcontroller and a RS-485 communication module. The calibration of a group of strain sensors was carried out in the laboratory environment for the verification of their functionality and reliability.

2 Overview of the smart strain sensor

2.1 Principle of the strain sensor

2.1.1 Strain gauge based measurement

Strain measurement based on resistive foil strain gauges has been widely used in industry. When the strain gauge deforms with the object in compression or tension, to which the strain gauge is firmly bonded, the resistance of the strain gauge changes simultaneously. In practice, the Wheatstone bridge configuration is usually used to facilitate the measurement of the resistance change, which is shown in Figure 1. The axial strain could be obtained with the following equation:

$$\varepsilon_F = \frac{4U_o}{2(1+\mu)U_{AC}K} \tag{1}$$

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where ε_F is the axial strain; μ is the Poisson's ratio of the material; U_o is the output voltage difference of the bridge; U_{AC} is the bridge excitation voltage; K is the gauge factor.

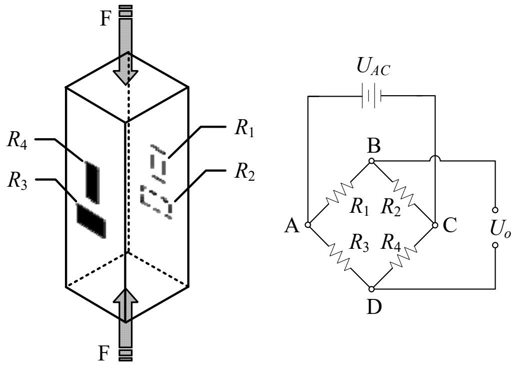

Fig. 1. Full-bridge Wheatstone bridge configuration.

2.1.2 Strain measurement with daisy chain scheme

The strain sensors can be networked in a daisy chain topology, which means the sensor nodes connect to a main cable trunk via short network stubs. Each sensor has a unique identifier. The typical arrangement of sensors in the static load testing of a pile is shown in Figure 2.

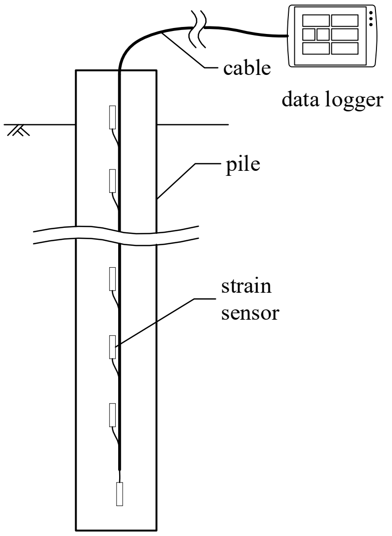

Fig. 2. Strain sensor network of daisy chain topology.

During testing, as the pile instrumented with the smart strain sensors undergoes strain in compression, the strain sensors would exhibit the same amount of strain. The internal measurement circuit can sense the voltage output difference of the Wheatstone bridge and convert it to strain readings. The data logger connected to the same main cable trunk could acquire the strain readings by polling the sensor nodes. The corresponding stress could also be obtained if the sensors are calibrated in advance.

2.2 Composition of the strain sensor

The smart strain sensor generally consists of a shell, two seal fasteners, a cable gland, and a key printed circuit board that does the measurement and communication. The structure of the strain sensor is shown in Figure 3.

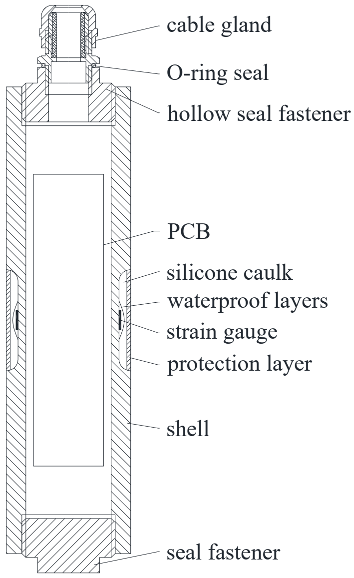

Fig. 3. Structural schematic of the strain sensor.

The shell of the strain sensor is made of the extensively used metallic material aluminium alloy 6061, which has fine characteristics such as good machinability, light weight and high resistance to corrosion. The middle part of the shell, where strain gauges are attached with adhesive, is made relatively thinner in order to increase sensitivity. Strain gauges could be attached to either the inner or the outer wall of the sensor shell; however, the outer wall is preferred in practice because it is much more conveniently accessible without the need for dedicated tools.

2.3 Strain gauge installation and protection

The strain gauge installation should be carefully taken care of, since it is crucial for the measurement accuracy and longevity of the final sensor. The procedures of installation mainly include degreasing, abrading and cleansing of the bonding surface for strain gauges, positioning and bonding of strain gauges, attaching wires and applying protective coatings. Cyanoacrylate, a type of general-purpose laboratory adhesive, is used for the bonding of strains gauges because of its fast room-temperature cure and ease of application.

As the strain gauges are attached to the outer wall of the sensor shell, the protective coatings should be able to insulate them from the adverse environment, especially from the underwater or humid environment. The waterproof structure for the strain gauges is shown in Figure 4, which consists of three different coating layers.

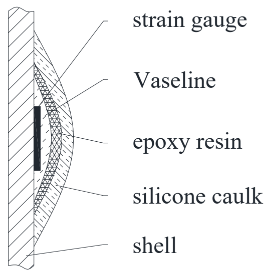

Fig. 4. Waterproof layers for the strain gauges.

The innermost layer, Vaseline, creates a waterproof barrier for the strain gauges and barely strengthen the local region of the shell. The intermediate layer is epoxy resin with fine mechanical and waterproof properties once fully cured, which can protect the strain gauges from damage to some extent. The outer layer of silicone caulk provides extra waterproof protection.

3 Hardware of the smart strain sensor

3.1 Circuit structure of the strain sensor

As a smart sensor, the strain sensor consists of a sensing element, and data acquisition and processing capabilities provided by a microcontroller. The output signal of the bridge circuit is fed to the signal conditioning module, which filters, amplifies and offsets the input signal. The output of the signal conditioning module is fed to the microcontroller with ADC, which converts the signal to strain and transmits response data to the host computer when polled. Besides, the digital output of the sensor provides good noise tolerance. The hardware block diagram of the strain sensor is shown in Figure 5.

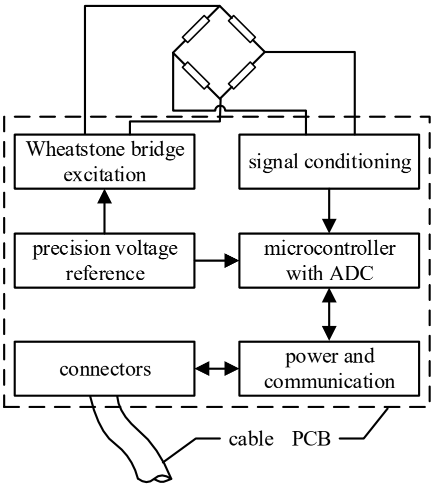

Fig. 5 Hardware block diagram of the strain sensor.

3.2 Circuit components of the strain sensor

As the prototype of the smart strain sensor needs a small measurement range, the Silicon Labs C8051F320, which is a fully integrated System-on-a-Chip MCU, is selected as the microcontroller. Its high-speed pipelined 8051-compatible microcontroller core (up to 25 MIPS) provides good processing capabilities. The true 10-bit 200 ksps single-ended/differential ADC with analog multiplexer is sufficient for the small measurement range. The enhanced UART serial interface implemented in hardware ensures stable communication.

The signal conditioning module consists of an AD620 and an OP2177. The AD620 is a low cost, low power, high accuracy instrumentation amplifier with low noise and low input bias current; only one external resistor is required to set different gains. A low pass R-C network is placed at the input of the AD620 to filter the disturbance signals. The OP2177 is high precision, dual operational amplifiers featuring extremely low offset voltage and drift, low input bias current, low noise, and low power. One of the dual amplifiers is used in the configuration of the Sallen-Key low-pass filter to provide offset to the AD620, the other drives a transistor for bridge precision excitation generation.

The output of the MC1403, which is a serial 2.5 V bandgap precision voltage reference with wide input voltage range and low quiescent current, is fed to the microcontroller and the bridge excitation module.

A low-power bidirectional transceiver MAX485 is used in the RS-485 communication module, which could cover cable lengths up to about 1,200 m. The in-process prototype of the smart strain sensor is shown in Figure 6.

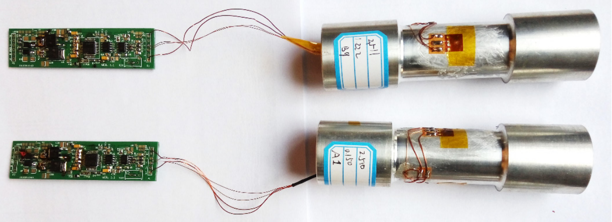

Fig. 6. A prototype of the smart strain sensor in process.

4 Force calibration of strain sensors

The direct output from the sensor is strain; however, measurement of force is desirable in some applications. Since the measured strain is proportional to the force, it is feasible that the strain sensor can be used to measure the applied force, provided a dedicated force calibration has been carried out in advance. For acquisitions of accurate force measurement results in practical applications, multi-point calibration is preferred to two-point calibration or one-point calibration.

4.1 Conditions of force calibration

The main equipment for force calibration includes a Gotech servo control system universal testing machine AI-7000M with a 20 kN load cell, a Gwinstek DC power supply GPC-3030DN, a USB-to-RS485 converter UT-890A, two controlling computers and dedicated accessories for sensor fixture.

The calibration of nine smart strain sensors, which were connected to a common 100 m cable at intervals of 7 m, was conducted in the lab at the room temperature of 20 °C. The output of the DC power supply is set at ±14 V.

4.2 Procedures of force calibration

Before calibration, the strain sensors were powered on for 15 min to stabilize. For the conduct of the multi-point calibration, the universal testing machine was manually programmed in advance to descend the load cell slowly enough to compress the strain sensor during the loading phase.

The initial output value of the strain sensor was recorded when no load was applied. After the setup was done, as shown in Figure 7, the controlling program of the universal testing machine started the compression procedure. When the actual load reached a predefined value, the loading process was temporarily paused, and the actual force applied and the output value of the strain sensor were recorded. Then the loading process resumed to the next loading level. The same calibration procedures repeated for all the predefined loading values for the strain sensor. Finally, the strain sensor was carefully unloaded and removed from the fixture.

Fig. 7. A strain sensor in the process of calibration.

4.3 Force calibration results and analysis

Typical calibration results and the corresponding fitted line plot of the strain sensor A1 are shown in Figure 8. The fitted line plot displays the relationship between the force actually applied to the sensor by the universal testing machine and the strain calculated with the data obtained from the sensor. The high adjusted R^2 suggests that the line fits the obtained experimental data well, thus the precision of coefficient estimates and predicted values are good.

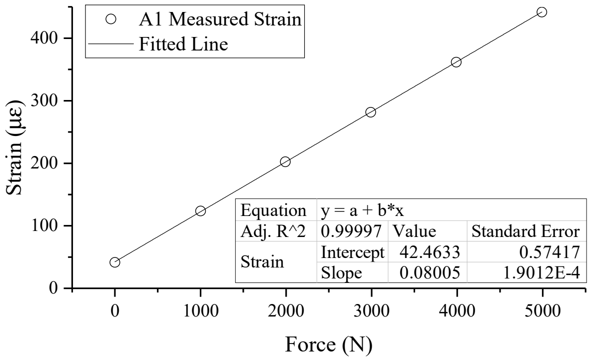

Fig. 8. Typical calibration results and the fitted line plot

The line fitting results of all the calibration data obtained from the nine strain sensors are shown in Table 1. The high values of adjusted R^2 suggest that all the strain sensors are of good linearity, and the values of slope suggest that their sensitivities are relatively close, just as expected. Besides, these sensors have some offset errors, whose influences could be easily eliminated in application.

Table 1. Line fitting results of strain sensors.

No.	Line equation	Adjusted R^2
A1	y=0.0801x+42.4634	0.99997
A2	y=0.0961x+221.2739	0.99995
A3	y=0.0935x+217.4764	0.99996
A4	y=0.0973x+318.4587	0.99995
A5	y=0.0990x+235.7962	0.99987
A6	y=0.0858x+436.3599	0.99996
A7	y=0.0891x+441.3942	0.99983
A8	y=0.0835x+330.6438	0.99990
A9	y=0.0860x+388.8736	0.99991

5 Conclusions

This paper introduces the development of a type of smart sensor that supports serial communication over RS-485 for the measurement of strain or stress of foundation piles, especially in static load testing. Apart from good noise tolerance, the sensor could share a common cable trunk in a daisy chain configuration, and the simple bus wiring and long cable length could save a lot of trouble during installation in the field. The compact and robust structure of the strain sensor and the reliable waterproof protections make the smart strain axial strain sensor suitable for harsh environment applications in geotechnical and civil engineering. The calibration results of a group of strain sensors showed their functionality and reliability.

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