WSN-based health monitoring of highway tunnel lining in seasonal cold region

Fei Du¹, Dongming Zhang², Yan Wu³, Hongwei Huang⁴ and Fushen Sun⁵

¹, ², ⁴ Department of Geotechnical Engineering, Tongji University, China, ³ Wisen Innovation Ltd, China.
⁵ Jilin Provincial Transport Scientific Research Institute, China.
² 09zhang@tongji.edu.cn

ABSTRACT

Wireless sensor networks (WSN) have attracted great attentions for structure health monitoring (SHM) in recent years. However, the application of WSN for monitoring tunnels in seasonal cold region still maintains big challenges in consideration of radio propagation and harsh environmental conditions. In this paper, a developed wireless sensor network is presented; the basic features of the hardware nodes and the WSN communication protocol are introduced briefly. A WSN system consisting of 37 nodes that can measure the inclination of the secondary lining was deployed in Laoyeling tunnel, which is a 2391m long stretch of NATM concrete-lined highway tunnel located in Jilin province, China. Over 5 months monitoring period, the network performances including the system reliability and the wireless network topology are analyzed. Furthermore, the paper illustrates the temperature and inclination monitoring results; the temperature distribution law of the surface of lining is presented according to the monitoring data, and the monitoring inclination data indicates that the lining deformation has been continuously evolving. This deployment demonstrates the feasibility and reliability of the presented WSN system for health monitoring of the long tunnels in seasonal cold region.

1. INTRODUCTION

Large numbers of highway or railway tunnels have been built in seasonal cold region around the world. The coldest monthly average temperature in some seasonal

¹ Graduate Student
² Assistant Professor
³ Engineer
⁴ Professor
⁵ Research Fellow
cold areas is lower than -20°C, in this case, the fissure and pore water of the surrounding rock mass of tunnel become frozen, as a consequence, expansion in volume occurs. This volumetric expansion is restrained by the tunnel lining and the unfrozen surrounding rock; therefore, the frozen rock results in forces on the lining, known as the frost-heave force of the surrounding rock. The frost-heave force and other forces acted on the tunnel lining may result in deformation or cracking and lead to some kind of frost damages. Moreover, the large temperature difference over a year will result in temperature stress in tunnel lining. During their lifetime, these tunnels inevitably deteriorate because of the frost damages and temperature stress, for example, 33 railway tunnels in the seasonal cold region of China have shown different degrees of frost damage (Lai 2000), so these tunnels require timely maintenance in order to prevent possible severe disruptions or accidents.

Structure health monitoring (SHM) is progressively being seen as an effective way to minimize identified or potential risks and is increasingly applied to civil infrastructures. Traditionally, manual monitoring and wired sensors network are applied to SHM, which have the disadvantages of low efficiency, high cost, long setup time and difficulties in cabling management. Especially, it’s a huge challenge for workers to conduct monitoring work due to the very low ambient temperature in cold environment. So it is badly in need of deploying an effective, reliable, large-scale, real-time and automatic monitoring system for civil infrastructures in seasonal cold regions.

In recent years, with the rapid advancement of sensor technology and wireless communication technology, wireless sensor networks (WSN) have attracted great attentions for SHM. The use of wireless sensors and wireless communication technique, which transmits the data using radio, allows a rapid and large-scale deployment due to elimination of the cables and self-organizing capability. Meanwhile, the improvement of micro-fabrication techniques has allowed the development of Micro-Electric-Mechanical system (MEMS)-based sensors that have the advantage of small volume, light-weight, high reliability, low-power dissipation and low cost. Combining the WSN with the MEMS-based sensors, there is the possibility for significant cost saving, long-term, real-time and automatic SHM. Straser and Kiremidjian (Straser 1998) are the first to illustrate the design of a low-cost wireless sensing unit intended for SHM, and they have validated the performance of their developed wireless sensing unit prototypes by installing five of them upon a 15m span of the Alamosa Canyon Bridge. Since then, numerous researchers have developed wireless sensors prototypes (Spencer 2004, Yu 2009, Ha 2013) and also have deployed sorts of WSN systems on bridges (Lynch 2003 2005, Chung 2004, Nagayama 2009) and urban metro tunnels (Bennett 2009 2010, Yin 2015, Wang 2016). Current research investigating the application of WSN for SHM has fewer focused on the infrastructures in seasonal cold region, and very fewer groups have deployed WSN in the long mountain tunnel with the goal of long-term monitoring. The application of WSN for mountain tunnels in seasonal cold region is still a huge challenge in consideration of radio propagation inside tunnel and the very low
temperature.

Together with the existing structural response indices that are common adopted in the SHM, i.e., acceleration, displacement and strain, the inclination change during structural deformation provides information that is useful in evaluating the deflection via the angle of rotation in the case of horizontal members and the drift in the case of vertical members. As such, an inclinometer can evaluate the deformation of members using the inclination, such that inclination measurements can be used as primary measures in evaluating the safety of individual structural members and entire structures (Ha 2013).

In this paper, a developed WSN is presented; the basic features of the nodes and the mesh network protocol are introduced briefly. A WSN system for measuring the inclination of tunnel lining was deployed in Laoyeling tunnel. A total of 37 nodes were installed, including 28 WSN tilt nodes integrated silicon capacitive MEMS-based inclinometer, 8 vibrating wire (VW) interface nodes and a WSN gateway. The paper describes the wireless network performance during the monitoring period. Furthermore, the monitoring data including the temperature data and inclination data are preliminary analyzed.

2. BASIC FEATURES OF WIRELESS SENSOR NETWORK SYSTEM

2.1 Nodes of WSN System

This paper presents a developed WSN system for structural inclination monitoring; the hardware of the system consists of WSN gateway and WSN tilt nodes, as shown in Fig. 1.

(a) WSN Gateway  (b) WSN tilt node

Fig. 1 Nodes of the WSN system

The WSN gateway (Fig. 1(a)) is used as a key unit in the WSN system. It is responsible for the command issuing, such as the sampling time interval and radio frequency modifications, and for data collection from all the nodes involved in a mesh network. Meanwhile, it transmits the data and system information to the remote server via mobile network or local server via standard RS232 connections. The WSN gateway
is powered by four 3.6V industrial D cell batteries, thus, the deployment of a WSN gateway can be more flexible from the traditional power supply cabling. To analyze the power consumption of the WSN gateway and WSN tilt node, laboratory experiments were carried out with the hardware settings including Keysight 34401A multimeter, Atten APS3005D power supply and PC. Fig. 2(a) shows the results of the power consumption analysis for the WSN gateway. The battery life of the WSN gateway increases linearly with the increase of the sampling time interval. Note that the battery life can be further extended by a factor of 1.5 if the WSN gateway is one-sixth times less often making connections to the server.

As the sensing devices in the WSN system, the WSN tilt node is as shown in Fig. 1(b), it is capable of sensing the inclination variation of the structure as well the working temperature, processing the measurements and transmitting the data packet via its internal radio module. The WSN tilt node consists of a MEMS-based dual axis inclinometer with the sensing range from -30° to 30°. Another key electronic component inside the WSN tilt node is a microcontroller with low power 2.4GHz transceiver that is compliance with IEEE 802.15.4 Standard. It is responsible for system controlling, data packets transmitting and receiving at 2.4GHz. To prevent physical damage to the inside electronic components by the harsh environment, the external component is constructed of aluminum-alloy with the size of 80mm×75mm×57mm and of IP66 protection from water and dusts. The 5dBi Omi-direction antenna with a length of approximate 200mm is used to provide longer radio communication range. A single 3.6V industrial D cell battery is used to power the WSN tilt node. The battery life of the WSN tilt node is closely related to the number of hops taking for a message to go through in the mesh networking. Fig. 2(b) shows the battery life calculated for a WSN tilt node taking no sub-mesh network and taking 9 hops of sub-mesh network of its own.

2.2 WSN Communication Protocol

In this study, the WSN communication protocol operating in the ISM 2.4GHz radio
band is designed based on the IEEE 802.15.4 wireless protocol standard. The radio frequency is between 2.405GHz and 2.480GHz with 16 channels (channel 11 to channel 26) of 5 MHz bandwidth at each channel. The transmit power is less than 1.4mW (i.e., 1.5dBm) typically with the minimum transmission rate of 250Kbit/s. The WSN communication protocol supports 10 hops network structure (e.g., the radio link from WSN gateway to the 1st layer node is called the 1st hop). The presented WSN possesses self-organizing capability to organize various network forms, such as ring network, mesh network, star network and line network etc. Single node environmental coverage has been measured and predicted using Modified 2D Finite-Difference Time-Domain (FDTD) method (Wu 2009); the results indicate that the communication distance is 100m at least while the antenna is placed at approximate 100mm away from the segments inside metro tunnel.

3. DEPLOYMENT OF WIRELESS SENSOR NETWORK IN HIGHWAY TUNNEL

3.1 Field Deployment Site

Jilin province is located in the northeast of China where the monthly average temperature is lower than 0°C from November to March of the following year; January is the coldest month when monthly average temperature is approximately -25°C ~ -20°C (China meteorological data service center, CMDC). The frozen earth type is seasonal frozen earth; the maximum frozen depth is approximately 1m ~ 3.5m over the years; in one year, the ground surface will be frozen in the latter of October, and the freezing period is about 112 days ~ 171 days (Zhou 2000).

Laoyeling Tunnel is a one-way and double lane tunnel with disjunctive up and down lines, located below Laoyeling Mountain in Jilin province. The tunnels were excavated by New Austrian Tunneling Method (NATM). Up and down line tunnel is 2360m and 2291m long respectively. Fig. 3 shows a geological longitudinal section alone Laoyeling down line tunnel. The maximum overburden depth of the tunnel is approximately 250m. There are three rock formations in Laoyeling Mountain passed through by the down line tunnel, the two main rock formations are alteration tuff and granite porphyry, the surface of the mountain is a relatively thick layer of clay containing reduced stones. There are four faults in the district alone the tunnel, as shown F1~F4 in Fig. 3, the tunnel gets through the fault F1, F2 and F4. The tunnel direction intersects these three faults at an angle of 60°~90°. Underground water consists of Quaternary pore water and bedrock fissure water, the overburden of the underground water is between 7.42m and 18.45m.
Fig. 3 Geological conditions and overburden in the tunnel

Fig. 4 shows a typical cross-section of Laoyeling down line tunnel. The tunnel section is a circuit arch having clear height of 7.1m and clear width of 10.6m. To support the tunnel section, composite lining was adopted. The primary support consists of steel fabric shotcrete and rock bolts; and the secondary lining was C30 reinforcing concrete. The PVC waterproof board and geotextile was lay between the primary support and secondary lining.

Fig. 4 Typical cross-section of the tunnel

3.2 Wireless Sensor Network Geometry
The network geometry design of WSN system adopted for Laoyeling Tunnel is shown in Fig. 5. A total of 37 nodes were installed; 28 WSN tilt nodes, 8 vibrating wire (VW) interface nodes and a WSN gateway. Note that the VW interface nodes using the same WSN communication protocol were deployed as relay nodes. The whole WSN system was deployed on December 14th and 15th, 2016. The WSN gateway was installed in the central of the tunnel, 1150m long away from west tunnel portal and 1140 long away from east tunnel portal. A total of five cross sections of secondary lining (MS1~MS5 in Fig. 5) were instrumented by four WSN tilt node at four locations alone the longitudinal direction of the tunnel. For each MS cross section, four WSN tilt nodes were installed at the arch springing and spandrel on the both sides of tunnel, the schematic diagram is shown in Fig. 5. The MS sections are spaced about 560m and 570m. Two WSN tilt nodes and two VW interface nodes spaced by 110m or 120m was installed between the two adjacent MS sections, allowing the wireless network using extensive hopping.

Fig. 5 WSN system deployment in Laoyeling Tunnel

When installed the nodes, plug bolts were used to fix the metal holder to the secondary concrete lining; then the nodes were fixed to the metal holder using bolt. Fig. 1 and Fig. 6 show the node prototypes after installation in site.
A mobile network is available in Laoyeling tunnel, meaning that the data packets from all the nodes can be transmitted to the remote server by the WSN gateway via mobile network. The sampling time interval of the WSN tilt nodes is 1 hour and the WSN gateway is one-sixth times often making connections to the server, i.e., 6 hours. According to the laboratory power consumption analysis, as shown in Fig. 2 and Fig. 3, the battery life of WSN tilt nodes and WSN gateway is at least 4029 days and 482 days in the worst case respectively. The battery life of the VW interface node is longer than WSN tilt node without measurement function. Thus, the deployed WSN system can monitor the lining structure for one year at least.

4 WSN SYSTEM PERFORMANCE

4.1 System Reliability

There are two main areas of concern when it comes to reliability of WSN system: hardware and radio connectivity (Bennett 2010). Because the ingress protection (IP) rating of all the nodes is more than IP66, the WSN deployments have not suffered from hardware failures even though the environmental conditions in Laoyeling tunnel are harsh.

The radio connectivity has experienced connectivity issues. The data packets transmitted from WSN gateway to remote server contain the information about the wireless sensor network connectivity, so that the radio connectivity quality can be evaluated. As mentioned before, the sampling time interval of WSN tilt node and the time interval taken for data packets from all nodes to reach the WSN gateway are both 1 hour (half an hour in the beginning). Ideally, the total number of data packets that each node should send to the WSN gateway is 2952 from December 14th, 2016 to April 19th, 2017. An indicator for the radio connectivity quality is the ratio of the number of data packet that is dropped (i.e. not transmitted) to the total expected number of packet transmitted. In this paper, the data loss ratio is defined by the Eq. (1):
$R_i(\%) = \left[1 - \left(\frac{T_{i\rightarrow G} - T'_{i\rightarrow G}}{T_{G\rightarrow i}}\right)\right] \times 100$  \hspace{1cm} (1)

where $R_i$ is the data loss ratio for node $i$, $T_{G\rightarrow i}$ is the counts of commands from WSN gateway to node $i$, i.e., the expected value of the number of data packet transmitted from node $i$ to WSN gateway, $T_{i\rightarrow G}$ is the actual number of data packet from node $i$ and $T'_{i\rightarrow G}$ is the repeated number of data packet from node $i$. The number of data packet from the nodes is counted at the WSN gateway, so the loss by traveling across several nodes to reach to the WSN gateway is also included in this ratio.

Fig. 7 Data loss ratio of nodes versus spatial distance to the WSN gateway

Fig. 7 shows the data loss ratio of all WSN tilt nodes and VW interface nodes with different spatial distance to the WSN gateway. The minimum data loss ratio is 0%, i.e., all the data packets of the node were transmitted to the WSN gateway, there are total 4 nodes with the data loss percentage of 0%, the maximum distance to WSN gateway of these 4 nodes is 350m. The maximum data loss ratio is 54.98%, i.e., 1612 data packets were dropped, this WSN tilt node was installed on the spandrel close to the east portal of the tunnel which is about 1130m apart away from the WSN gateway. In general, the data loss ratio increases with the spatial distance to the WSN gateway, there are 6 nodes whose data loss ratio is more than 15%, and the distance to the WSN gateway of these 5 nodes is more than 1000m. Shortening the distance between the WSN gateway and the nodes is an effective way to decrease the data loss ratio.

Fig. 8 shows the percentage of the nodes with different data loss ratio, the number in bracket is the data loss ratio range. For the deployed WSN system with only one WSN gateway, there are 63.9% of all the nodes, i.e., 23 nodes, whose data loss ratio are less than 5%, whereas, 16.7% of all the nodes (6 nodes) whose data loss ratio are more than 15%.

Beyond doubt, for the long tunnel WSN monitoring, two effective solutions to reduce the amount of the nodes with large data loss ratio would install more WSN gateways or install more relay nodes so that the distance between adjacent nodes can be shortened, but this increased reliability comes with a subsequent increase in cost use.
4.2 Network Topology

Based on the layout of the whole WSN system, there are many possible routes that individual data packet could take from the node to the WSN gateway. The network topology can demonstrate the traveling route of the data packets for a specific node. At different moment, the network topology will differ due to the external conditions and passing of vehicles. Fig. 9 shows two different network topologies at two different moments. The filled circle represents the WSN tilt nodes; the filled square represents the VW interface nodes, and the filled pentagram is the WSN gateway. The number beside the nodes is the node ID. The outside two rows of the nodes were installed on the arch springing, and the other two rows of the nodes were installed on the spandrel, as shown in Fig. 5 and Fig. 6.

These two figures both illustrate that the WSN system uses multi-hop routing to transmit the data packets. The cyan solid arrows are the radio link from 5th hop nodes, the green solid arrows are the radio link from 4th hop nodes, the red solid arrows are the radio link from 3rd hop nodes, the blue solid arrows are the radio link from 2nd hop nodes, and the black solid arrows are the radio link from 1st hop nodes, that is, the radio link from the nodes to the WSN gateway. Fig. 9(a) shows that all the nodes were online and there were 5 hops at this communication moment, whereas, as shown in Fig. 9(b), at 23:19 April 18th, 2017, 44% of all the nodes, i.e., 16 nodes were online and there were 4 hops, the rest of the nodes were offline. It is necessary to note that a node was offline at a certain moment doesn’t mean that the data packet was dropped; this unsent data packet would be stored in the data memory of this node and would not be transmitted until the node was re-online. However, the node will automatically reboot if the offline time is more than 24 hours, the reboot of a node comes with a subsequent that the data stored will be eliminated, that is, the data packets are dropped.
The data packet from a node has both a parent node ID and a node ID. From this information, it is feasible to compute the probability of each link between nodes. The probability of the link from node $i$ to node $j$ is introduced using the Eq. (2):

$$P_{i \rightarrow j} = \frac{n_{i \rightarrow j}}{N_i}$$

where $P_{i \rightarrow j}$ is the possibility of the link from node $i$ to node $j$ (including the gateway). $n_{i \rightarrow j}$ is the number of data packets transmitted from node $i$ to node $j$. $N_i$ is the total number of the data packets which are transmitted from node $i$.

Fig. 10 shows the most likely communication links. The red thick solid arrows are the links with a probability of above 50%, whereas the black thin solid arrows are the links with a probability between 10% and 50%. This figure illustrates that the communication between nodes is quite busy and complicated; all the nodes provide different possibilities for routing. As can be seen from Fig. 10, the nodes that are located on the same side with WSN gateway are more likely to relay the data packets, such as node A46C, node 22FF and node A015 etc., this appearance occurs due to passing of vehicles will influence the direct communication between WSN gateway and nodes that are located on the opposite side with the WSN gateway. In general, the WSN communication protocol makes nodes to communicate directly to the WSN gateway if possible, consequently, closer to the WSN gateway doesn’t mean the more possible to be a relay node, for instance, the node 222C compares with the node 2329. The data packets are hopped to the WSN gateway when the nodes cannot communicate directly to the WSN gateway, thus, the nodes located away from the WSN gateway tend to send
the data packets to one of the WSN tilt nodes or VW interface nodes and then the selected node transmits the data packets to the WSN gateway or another node.

![Diagram](image)

Fig. 10 Network topology showing the most likely routes (red thick solid arrows: links with a probability of above 50%; black thin solid arrows: probability of below 50% and above 10%; ●: WSN tilt node; ■: VW interface node; ★: WSN gateway)

5. MONITORING RESULTS OF WSN SYSTEM

A certain number of data packets including temperature and inclination information have been measured by the deployed WSN system. The variation rules of temperature field in tunnel can be obtained according to the temperature monitoring data. Some WSN tilt nodes of the MS sections (shown in Fig. 5) do measure the movements of the secondary lining. Before the installation of the WSN tilt nodes in site, the temperature experiments have been already conducted for build the temperature compensation model to eliminate the performance degradation of the WSN tilt node due to temperature fluctuations.

5.1 Temperature Monitoring Results

The temperature field of the lining and surrounding rock of tunnel is the key factor for the tunnel design in seasonal cold region. The variation rules of temperature field in tunnel can be obtained through the temperature monitoring data. Shown as Fig. 1(b), the WSN tilt nodes of the five MS sections were installed on the lining with the distance about 5cm away from the surface of lining. In this paper, the monitoring temperature is regarded as the temperature of the surface of lining.

For each MS section, the temperature of the surface of lining is the mean value of the temperature value measured by all four WSN tilt nodes. Fig. 11 shows the temperature distributions of the surface of lining in different month along the longitudinal direction of the tunnel. In December, January and February, that is, in cold season, the temperature of the surface of lining follows the same distributional trends in the longitudinal direction, that is, the parabola distribution. The temperature increases from the two sides of the portal to inside of the tunnel, however, the temperature distribution is not symmetrical, the distance of the cross-section with the highest temperature to the east tunnel portal is approximate three quarters of the tunnel length. What's more, the
temperature closed to the west tunnel portal is high than the temperature closed to the east tunnel portal. The temperature is the coldest in January, when the coldest monthly average temperature of the surface of the lining is approximately -16°C, and the largest temperature difference along the longitudinal direction is approximately 6°C. In March and April, temperature distributions are not parabolic distribution, the temperature difference along the longitudinal direction of the tunnel becomes smaller and smaller, the temperature of the surface of lining almost linearly increases from the east portal to the west portal with the gradient of 0.0012°C/m in March, and in April, the temperature along the tunnel length is almost equal.

![Fig. 11 Lining temperature along the tunnel longitudinal direction](image)

### 5.2 Inclination Monitoring Results

In the case of rocks surrounding ground, there are gaps and spaces remained between the lining and surrounding rock, such gaps or spaces are caused by uneven excavated face and primary support which consists of shotcrete, rock bolts and lattice girders. For the rock tunnel in seasonal cold region, the water filling in the gaps and spaces will be frozen up in cold seasons; the frost-heave pressure will come into being due to the frost swelling confined by rock and lining (Wang 2004). Moreover, the temperature difference over a year and at different cross-sections will result in temperature stress in tunnel lining (Luo 2010). The lining of the tunnel in seasonal cold region will deteriorate under the frost-heave pressure, freeze-thaw cycles effects (Tan 2013, Feng 2015) and temperature stress, and thus, the lining is more likely to be deformed. The inclination of the lining can reflect the entire deformation and evaluate the safety of the tunnel to some extent.

The results for 5 months from MS1 section are shown in Fig. 12; the inclination data have been compensated. The data shows the change in the readings from the WSN tilt nodes since they were installed. The location of the WSN tilt nodes is shown in Fig. 13. As the Fig. 12 shows, three installed WSN tilt nodes do measure the inclination change of the lining, but the inclination change values are no more than 0.1°. Fig. 13 shows the movement direction (the dashed arrow: rotation direction at previous stage,
the solid arrow: rotation direction at later stage) and the inclination change value (the numbers beside the nodes) from the installation time to 30th April, 2017. The lining measured by node A18C and node A3BB have rotated in one direction, while lining measured by node A3BE have rotated in two different directions, and the lining measured by node A38B have not rotated.

![Graph showing inclination change over time](image)

**Fig. 12** Inclination monitoring results of MS1 section

![Diagram showing movement](image)

**Fig. 13** Movement measured of MS1 section (View from Chang Chun side)

The movements for all other MS sections are summarized in Fig. 14. The movement trends of different MS sections are different. At present, it is difficult to determine the exact mechanism of tunnel movement from the readings taken to date, which exactly is the future work of this study.
6. CONCLUSION

This paper presents a developed WSN system for structural inclination monitoring, the hardware nodes of the system mainly consist of the WSN gateway and WSN tilt node, the WSN communication protocol is designed based on the IEEE 802.15.4 wireless protocol standard and operates in the ISM 2.4GHz radio band. The basic features of this WSN system are introduced briefly. The WSN system possesses the advantage of ultra-low power consumption and artificial intelligence self-organizing.

In order to realize the real-time, automatic, long-term and remote health monitoring for a highway tunnel and demonstrate the applicability of the presented WSN system in seasonal cold region. A WSN system including a WSN gateway, 28 WSN tilt nodes and 8 VW interface nodes was deployed in Laoyeling tunnel in seasonal cold region of China. Up to now, the WSN system has been operating normally without any hardware failure. The data loss ratio is proposed to evaluate the quality of radio connectivity between the nodes and WSN gateway. By calculating the data loss ratio, the radio connectivity between the nodes far away from the WSN gateway and the WSN gateway is an issue even though there are many relay nodes with the interval of 110m or
120m. The maximum data loss ratio is 54.98%, and the data loss ratio of 36.1% of all nodes (13 nodes) is more than 5%. For the long tunnel monitoring, more than one WSN gateway should be installed in site besides the installation of relay nodes to reduce the quantities of the dropped data packets. The WSN system uses multi-hop routing to transmit the data packets; the communication between nodes is quite busy and complicated. Sometimes, all the nodes were online, which can insure that all the data packets can be transmitted to the WSN gateway, while some nodes were offline due to the influence of some external conditions such as passing of vehicles. In general, the WSN communication protocol makes nodes to communicate directly to the WSN gateway if possible, consequently, some expected relay nodes closed to the WSN gateway can’t relay the data packets frequently. Thus, it is not necessary to deploy the relay nodes near the WSN gateway.

A certain quantity of data has been measured by the deployed WSN system for almost 5 months. According to the monitoring results, the temperature distribution of the surface of lining follows the parabola distribution along the longitudinal direction of the tunnel in cold seasons, the temperature increases from the two sides of the portal to inside of the tunnel. The temperature monitoring results can be used for the mechanical analysis as the boundary conditions.

The compensated inclination monitoring results do indicate movements of the tunnel lining even though the magnitudes of the inclination change value are no more than 0.1°. The magnitudes and the rotation direction of all five monitoring sections are different as the movement of the lining is complex. In the future, the mechanism of tunnel movement will be studied; evaluating the health condition through the inclination of the lining is also a valuable work.

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