Wireless sensing on shield tunnels in Shanghai

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ABSTRACT Recent years more and more shield tunnels are being used in urban critical infrastructure in China, such as road and metro tunnels. Its safety during the construction and operation should be most crucial. Monitoring the tunnel behaviour including deformation, water leakage, crack and damage and etc is an effective way to control the lifetime safety of shield tunnel. In this paper, a "smart" sensing system coupling the tilt sensor, seepage sensor, and crack sensor with MEMS-based and Zigbee-based Topological network and their application in road and metro shield tunnel are firstly proposed in China. All these sensors were developed and validated by indoor model test for shield tunnel segmental lining structure. MEMS tilt sensors were installed in 2 sections of the Shanghai Dalian road shield tunnel with 11m outside diameter and 480mm segment thickness. Tilt, seepage and crack sensors were installed in one interval shield tunnel in Shanghai metro with 6.2m outside diameter and 350mm segment thickness. The lateral convergence transferred from tilt sensor, area of seepage, opening and closing of joints can be obtained by WSN. Both measured data shows their stable and reliable. The merit of this system, compared to the conventional monitoring system, is its ability of real-time dynamic monitoring regardless of the running of road or metro tunnel.

1 INTRODUCTION

As the urban metro network rapid expanding, more and more structure diseases also emerge, i.e., large convergence, differential settlement, crack and seepage. Most of these structure diseases occur due to poor soil condition, poor workmanship, and adjacent construction and so on.

Structure Health Monitoring of the urban metro tunnel is necessary to understand the safety state of the operated tunnel. For an operated tunnel in a normal condition, the monitoring plan is the measurement of horizontal convergence by using the traditional monitoring system, e.g., total station (Bakker, et al., 1999). The frequency of the measurement is twice a year. In the meanwhile, the structural defects, such as leakage, joint open and segmental dislocation, are items of the traditional manual inspection plan for the metro tunnel with a frequency the same with that of convergence (Richards, 1998, Yuan, et al., 2012, Llanca, et al., 2013). However for the urgent condition, the real time monitoring should be conducted for the early warning. In recent years, micro-electro-mechanical systems (MEMS) and wireless sensor network (WSN) are popular for structure health monitoring in civil engineering. As the technology evolving, MEMS sensors have become more integrated and less power-consuming which is ideal for its combination with WSN. Bennett et al. (2010) have applied several WSN trial systems in London, Barcelona and Prague subway tunnels. The battery powered sensor modules are small, completely wireless and easy to install. They automatically construct the network topology and acquire high quality live data 24 hours a day. Huang et al. (2012) discuss the WSN employed for the behavior study of shield tunnel structure. A wireless MEMS inclinometer prototype is developed for urban metro tunnel by Tongji University(He, et al., 2013), meanwhile a model for calculating the tunnel convergence was developed using this MEMS sensor (Huang, et al., 2013). A wireless crack sensor is developed for joint opening monitoring in shield tunnel (Wang and Huang, 2013). Seepage of shield tunnel is monitored by wireless sensor using Electrical Conductivity Method (Cheng and Huang, 2014).

This study presents a "smart" sensing system coupling the tilt sensor, seepage sensor, and crack sensor with MEMS-based and Zigbee-based Topological network and their application in road and metro shield tunnel are firstly proposed in China. Meanwhile the feasibility of WSN in metro shield tunnel is also discussed.

2 DEVELOPMENT OF WIRELESS SENSOR NETWORK FOR SHIELD TUNNEL

2.1 *Wireless sensor*

2.1.1 *Tilt sensor*

TJ-UWIS is a series of MEMS inclinometer prototypes developed by Tongji University. Three different specifications of TJ-UWIS sensors are provided for various purposes. There are single axis analog inclinometer (V1.3), dual axis analog inclinometer (V1.1) and single axis differential inclinometer (V1.2). The TJ-UWIS is compatible with our own wireless smart sensor network.

A series of tests are conducted in order to inspect the MEMS sensor's adaptability to various environments. All the sensors are tested under the same condition to compare their performances. Table 1 shows the performance indexes of TJ-UWIS.

Table 1. Performance index of TJ-UWIS

	Axis	Precision (º)	Resolution (º)	Range (º)
TJ_UWIS1.1	2	0.01	0.0025	-90~90
TJ_UWIS1.2	1	0.01	0.0025	-30~30
TJ_UWIS1.3	1	0.01	0.0013	-30~30

2.1.2 *Seepage sensor*

Electrical Conductivity Method is used to develop the seepage sensor. The concrete is almost non-conductive when concrete is dry. However when concrete is soaked by water, its conductivity increases rapidly and resistance reduce greatly. Based on the concrete resistivity change characteristics, the tunnel leakage can be detected. Figure 1 shows the relationship between current and time under different flow rate.

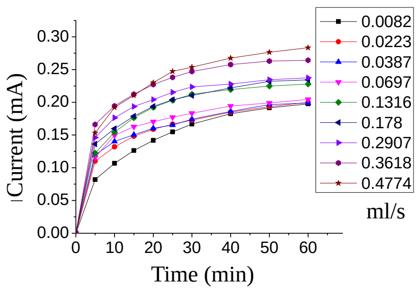

Figure 1. Current-time curve of different flow rate

2.1.3 *Crack sensor*

The structure of wireless crack sensor mainly consists of displacement transducer, temperature sensor, AD convertor, microcontroller and power module (Figure 2). The displacement transducer, LPDT or LVDT, has small range and high precision. The temperature sensor is used for temperature compensation.

The microcontroller combines the excellent performance of a wireless transceiver (based on Zigbee protocol) with an industry-standard enhanced micro control unit. It has various operating modes, including ultralow power-consumption operating mode, making it have advantages in terms of power consumption and data rate. A series of tests are conducted in order to inspect the crack sensor's adaptability to various environments.

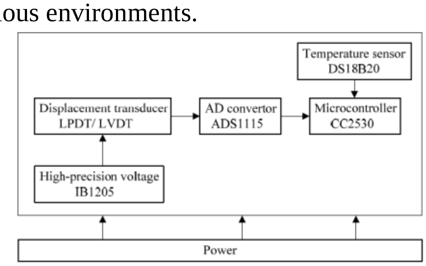

Figure 2. Structure of wireless crack sensor

2.2 *Wireless Sensor Network Deployment*

We deployed a WSN in a Shanghai shield tunnel. Figure 3 shows a model of the tunnel and the sensor nodes deployed. Here the base station is 20 meters away from the tunnel entrance, and is perpendicular to the tunnel mouth. An algorithm is proposed for the temporal and spatial compression and recovery of sensor data in the complex environment of a shield tunnel.

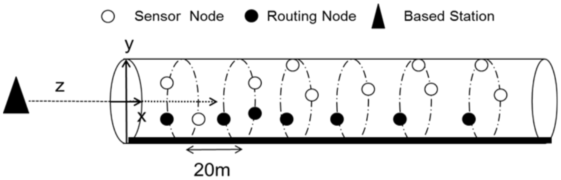

Figure 3. WSN deployment in a shield tunnel

3 MODEL TEST

Figure 4 shows the experimental facility in working condition. It includes two segments from a shield tunnel ring. The test-piece is fixed on two hinge supports which limit the linear displacement while rotation is allowed. Three horizontal hydraulic jacks are applied to simulate axial force in the ring. Vertical load is applied by a series of beams powered by another three jacks.

The convergence displacement of shield tunnel has a functional relation with its inclination. The mid-span displacement can be calculated by following equation based on inclination data.

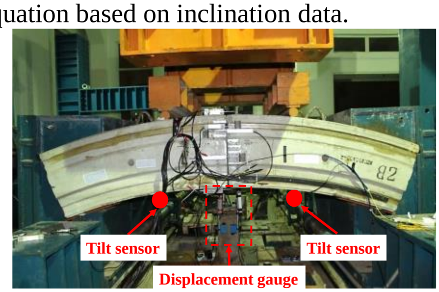

Figure 4. The experimental facility

$$a_{cs} = \frac{AC^2[\sin(\alpha_0) - \sin(\alpha_0 - I_{1s})] + BC^2[\sin(\beta_0) - \sin(\beta_0 + I_{2s})]}{AC + BC} \quad (1)$$

where α_0 = arctan (f/L_1), β_0 = arctan (f/L_2) as shown in Figure 5. The result will be compared with the real mid-span displacement measured by conventional instruments.

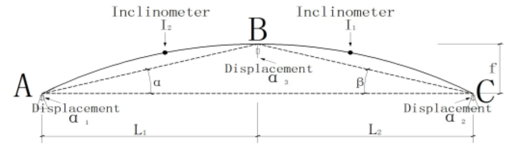

Figure 5. Sketch of the test-piece segment

Figure 6 shows the calculated displacement from the wireless inclinometer and the reference displacement from displacement gauges of each stage of load. The average error of the calculated displacement is about 7% which is acceptable. Although the variance of the calculated displacement is relatively large, indicating that the readings of the inclinometer are shifting constantly, they still spread evenly around the true value.

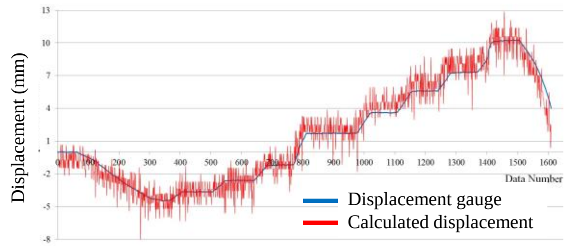

Figure 6. Calculated displacement by Tilt sensor

4 CONVERGENCE CALCULATION FOR SHIELD TUNNEL

The ring of shield tunnel is composed of several segments, shown in Figure 7.

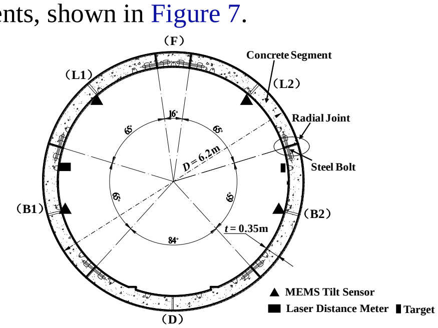

Figure 7. Cross section of metro shield tunnel

A simplified model is developed for calculating the horizontal convergence assuming that the segment is rigid, that is, tunnel deformation mainly consists of the joints rotation. Figure 8 presents the geometry model for the shield tunnel deformation. The horizontal convergence of tunnel can be calculated by Equation 2.

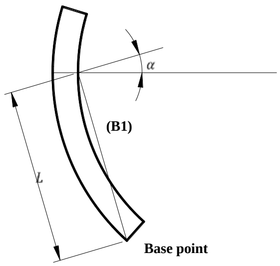

Figure 8. Geometry model of shield tunnel deformation

$$\Delta D' = L \times (\Delta\theta_1 - \Delta\theta_2) \times \cos\alpha \qquad (2)$$

where $\Delta D'$ is the change of horizontal convergence, L is the distance from the base point to inner surface at the tunnel center point level, $\Delta\theta_1$ is change of the tilt sensor on segment B1, $\Delta\theta_2$ is change of the tilt sensor on segment B2, α is the angle shown in the Figure 8.

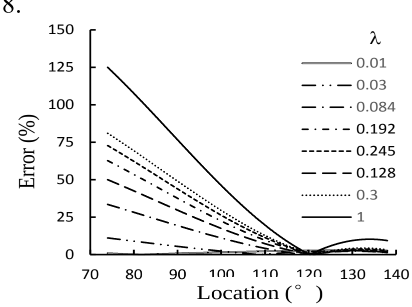

Figure 9. Calculation error at different measurement location

Considering the segmential lining is deformable, the calcultion error by Equation 2 is analyzed using K.M. Lee model under various joint stiffness, shown in Figure 9. Result indicates that the best installation point for tilt sensor is 120° (setting the crown of tunnel as 0°).

5 CASE STUDY

5.1 Case 1 for Shanghai Metro tunnel

Because of extreme surcharge loading on the ground surface above the metro tunnel, several serious diseases including large convergence, crack, and seepage occurred in the shield tunnel structure are observed. In order to ensure the safety of tunnel operation, the convergence performance is recovered by soil grouting at two sides of the tunnel lining. WSN is employed for the behavior study of shield tunnel structure during the soil grouting. Applications of convergence monitoring by MEMS Tilt sensors are illustrated.

Tow monitoring section, that is, ring 411 and ring 433, were selected to measure the convergence development during the soil grouting. The segmental lining for this metro tunnel has an outer diameter D of 6.2 m and a thickness of 0.35 m, as shown in Figure 7. One tilt sensor was installed on the inner surface of lining L1, B1, L2 and B2. Four MEMS tilt sensors are installed within one ring in total. Meanwhile one laser distance meter sensor was installed on B1 at the same level of tunnel center. Target for laser distance meter was installed on B2 at the same level.

Tilt sensors measure the rotation of segmental lining during the soil grouting. Figure 10 shows the tilt data of Ring 433 on 18th June, 2014. Figure 11 shows the tilt change and its direction of segmental lining after one night soil grouting. It indicates that the horizontal convergence become smaller during the grouting.

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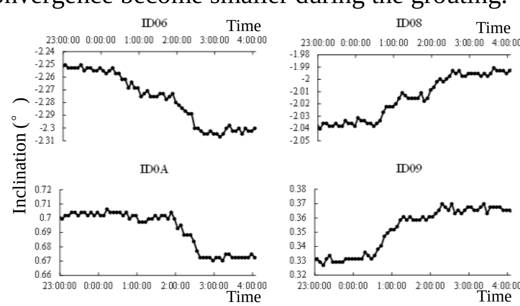

Figure 10. Tilt data of Ring 433 on 18th June

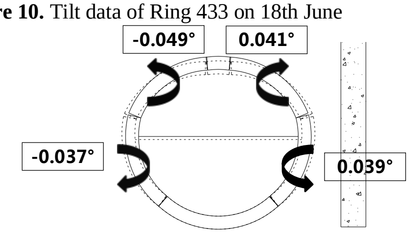

Figure 11. Schematic of segment rotation of Ring 433

The calculated change of horizontal convergence of Ring 433 due to one night grouting is -3.057 mm on 18th June. Laser distance meter and total station are conducted to verify the results. The change of horizontal convergence measured by laser distance meter and total station is -3 mm and -3.1 mm, respectively. For Ring 411, the calculated change of horizontal convergence is -2.735mm on 18th June, and the measured data by laser and total station is -2 mm and -3.7 mm, respectively.

5.2 Case 2 for Shanghai Metro tunnel

There is a deep excavation for a business plaza nearby Shanghai metro, which would impact the tunnel safety. The nearest horizontal distance between the tunnel and deep excavation is 9.46 meters. The soil grouting is conducted for protecting the tunnel. To verify the best installation point, the tilt sensors are installed at 100° (setting the crown of tunnel as 0°), 120° and 137°.

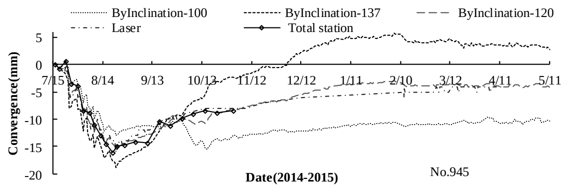

Figure 12. Calculated convergence by tilts at different location

The convergence calculated by tilt sensor at 100° and 137° are much different from the convergence measured by laser displacement gauge and total station. However the convergence calculated by tilt sensor at 120° agrees with the conventional method very well. The result prove that 120° is a best installation point of tilt sensor for convergence monitoring.

During grouting period, the convergence reduced about 16 mm. After grouting, the soil rebounded and the convergence kept stable at 5mm nearly. The grouting improved the soil condition and the grouting effect for convergence is about 5mm finally.

5.3 Case 3 for Shanghai Metro tunnel

Comprehensive demonstration for tilt sensor, seepage sensor and crack sensor is conducted in one section of Shanghai metro tunnel. The range of this demonstration is about 540 m from Ring 555 to Ring 1005. The distance between two monitoring sections is 12 m, 24 m and 36 m depending on the tunnel condition, shown in Figure 13.

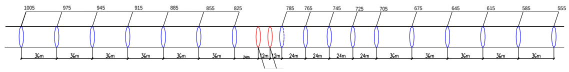

Figure 13. Monitoring sections along the shield tunnel

There are 30 tilt sensors, 4 seepage sensors and 8 crack sensors installed with two gateway to set up the wireless sensors network in total. Figure 14 shows the convergence change during one month. It is about 0.2 mm deformation in total and the convergence keep decrease during this period. The radial joint opening of Ring 765 is obtained by crack sensor. The displacement of joint is fluctuant around 0.25 mm, shown in Figure 15, which could be impacted by the vibration of running train. Circumferential joint and radial joint of Ring 765 is monitored for seepage. When the voltage of seepage sensor is above 0.1 V, there is seepage at the joint. Figure 16 indicates that there is seepage at the circumferential joint but the radial joint.

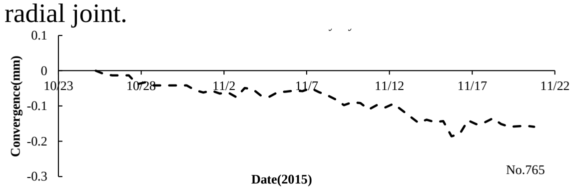

Figure 14. Convergence change of Ring 765

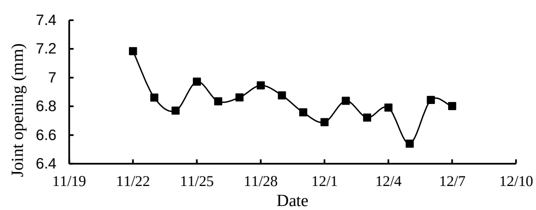

Figure 15. Opening of radial joint in Ring 765

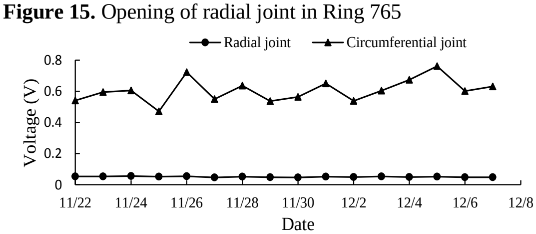

Figure 16. Seepage monitoring of Ring 765

5.4 Case 4 for road tunnel

MEMS tilt sensors are installed in 2 sections of the Shanghai Dalian road shield tunnel with 11m outside diameter and 480mm segment thickness. The tunnel ring consists of 8 segmental lining, shown in Figure 17. Six tilt sensors are installed subject to the tunnel site condition. Figure 18 shows that the total change of tunnel convergence is about 2 mm during the year. It is stable from January to June. However the convergence increases obviously in summer. After summer it goes back partially.

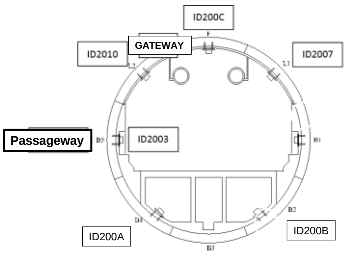

Figure 17. Cross section and tilt sensor installation of road tunnel

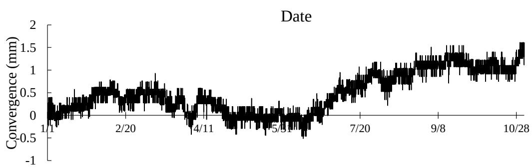

Figure 18. Convergence change of road tunnel during 1 year

6 CONCLUSION

In this paper, a "smart" sensing system coupling the tilt sensor, seepage sensor, and crack sensor with MEMS-based and Zigbee-based Topological network is developed, according to the characteristics of the tunnel structure and environmental conditions. A series of tests show that the sensors have good performance and adaptable to various environments.

A simplified model is developed to calculate the change of tunnel horizontal convergence using the tilt data. The best installation point is also recommended for Shanghai metro tunnel. According to the comparison result with conventional method, this model is good enough for field application. Furthermore this method can obtain the real time performance of operated tunnel to ensure the safety of tunnel operation.

Four cases of the "smart" sensing system application in road and metro shield tunnel are firstly proposed in China. This system is improved significantly during these applications. So far, a huge site of 251 monitoring sections have been installed in Shanghai metro tunnel with length of 20 km. There are 518 tilt sensors and 20 gateways to compose the system. The intervals of monitoring section are 36 m, 60 m and 120 m, depending on the deformation history and tunnel condition. This system is still in testing phase and the testing data analysis is ongoing.

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