The Real-Time Monitoring System for Metro Shield Tunnels: From Research to Application

Jinfeng Zhang, Wangsheng Liu, Ming Zhao

THE REAL-TIME MONITORING SYSTEM FOR METRO SHIELD TUNNELS: FROM RESEARCH TO APPLICATION

Jinfeng Zhang[1], Wangsheng Liu[1], Ming Zhao[1]

1. College of Civil Engineering, Tongji University, Shanghai 200092, China

zhaom@tongji.edu.cn

ABSTRACT

To the tunnel structure in soft soil foundation, damages are likely caused by large deformation, thus it is more reasonable to measure deformation than to measure force or stress. Although there are many ways to obtain deformation information, measuring inclination of segments is one of the most effective ways, and it is convenient to derive the deformation from the inclination data. The method to obtain the variation of tunnel's diameter, the opening length of longitudinal connecting seams, the concrete stress of bolt and certain joint is studied in this paper by making use of the inclination variation of lining segments. This paper outlines a real-time monitoring system based on the internet of things which will be applied to an interval shield tunnel of Shanghai metro line 12 this year.

KEYWORDS: *Metro shield tunnels, Inclination variation, Optimal position for inclinometer, Real-time monitoring system.*

INTRODUCTION

With the increase of the service life of existing metro shield tunnels, some sorts of damages, such as leakage, crack, settlement, deformation, will appear inevitably. Numerous long-term monitoring systems have been designed and implemented for civil and transportation infrastructures worldwide such as high-rise buildings, long-span bridges, and high-speed rails [1-4], while the applications of health monitoring technology to underground structures during construction and operation have not been widely exploited and put into practice [5-7].

Due to the long inspection period of conventional monitoring approaches, it is difficult to monitor the operation of metro shield tunnels in a real-time and in an effective way. To ensure the safety of metro tunnel, it is of great significance to build a real-time monitoring system for metro tunnel structure based on the internet of things.

1. RESEARCH PRIMED FOR APPLICATION

1.1. Optimal Position for Inclinometer

Shield tunnel will occur deformation under the effect of various factors, and whatever reasons for the deformation, the relative spatial relation between each segment of the lining ring accords with certain rules, as well as the variation of each segment's inclination.

Obviously, the inclination variation of each segment is different, so it is necessary to determine the most sensitive position of the inclination variation to the deformation of the lining rings, in other words, to determine the position of the inclinometers. In this paper, ABAQUS software is used to set up a finite element model, and to extract the inclination variation of each element.

1.1.1 Finite Element Model

A lining ring of Shanghai metro shield tunnel is 6.2m in outer diameter, 5.5m in inner diameter and 1.2m in length. It is composed of six parts: one top block, two adjacent blocks, two standard blocks and one bottom block. Because of symmetry, we only take 1/2 of the lining rings for analysis, and the constraints are imposed on the surface of the symmetry.

Element selection and its constitutive relations are as follows:

Concrete is simulated using three-dimensional eight-node entity element C3R8. The constitutive relation adopts concrete plastic damage model, its failure criterion parameters are shown in table 1. The uniaxial ultimate tensile strength adopts 2.74Mpa, and the uniaxial ultimate compressive strength adopts 35.6Mpa.

Table 1: The failure criterion parameters of concrete plastic damage model

Parameter	Value
Dilatancy angle	35°
Eccentricity ratio	0.1
The ratio of biaxial ultimate compressive strength and uniaxial ultimate compressive strength	1.25
Constant stress ratio	0.66667
Cohesion coefficient	0

Reinforced steel is simulated using three-dimensional two-node link element T3D2 and bilinear ideal elastic-plastic constitutive relation, with the elastic modulus $E_s = 2.00 \times 10^5 MPa$, with poisson's ratio $\mu = 0.3$, with longitudinal reinforcement's yield stress $f_{y1} = 335MPa$ and with stirrup's yield stress $f_{y2} = 235MPa$. Use the embedded element to simulate the bonding relation between steel and concrete.

Bolt is simulated using element T3D2, and its constitutive relation is elastic-plastic.

1.1.2 The Finite Element Analysis Results

Analysis results show that there are three kinds of failure modes: the opening and dislocation of longitudinal connecting seam, tensile failure of bolt at joint No.1 and No.2, and compressive failure of concrete at joint No.1. The vertical displacement contours of limit state are shown in figure 1.

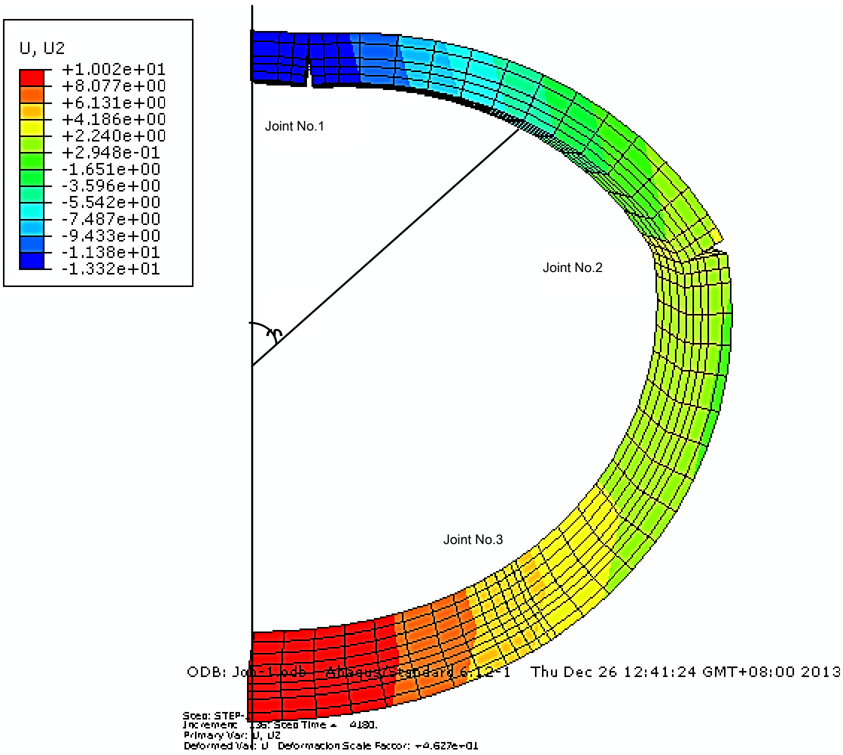

Figure 1: The vertical displacement contours of limit state

The inclination variation of each node can be calculated through the extraction of the node coordinates in the initial and limit state respectively. In the end, the relationship between the location and the inclination variation of elements is obtained, as shown in figure 2.

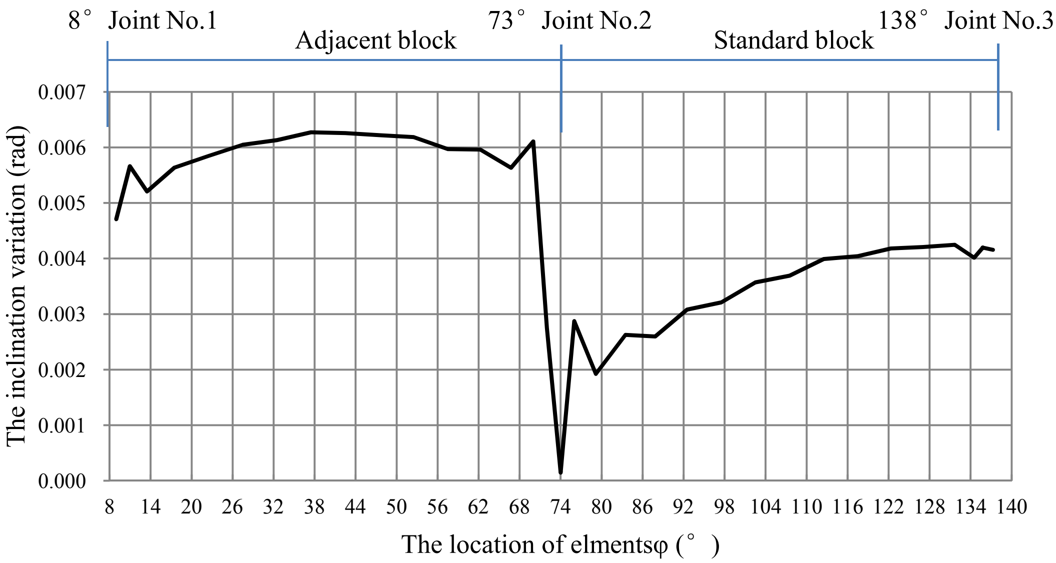

Figure 2: The relationship between the location and the inclination variation

We can get the following conclusions through analyzing the chart above:

(1) The inclination variation of each element in the adjacent block is 0.0056~0.0063rad and that of in the standard block is 0.0026~0.0042rad. The inclination variation of all elements within adjacent block is almost the same, and is obviously larger than that within standard block.

(2) The largest inclination variation of elements within adjacent block locates in the angel of 45°, with the value of 0.0063rad. Compared with the precision of 0.0001rad of the inclinometer, the installation of sensors at this location can well reflect the deformation of the lining ring.

(3) The inclination variation of elements nearby the longitudinal connecting seams is small and irregular, and considering certain problems, such as stress concentration, the installation position of sensors should avoid the joints.

1.2. Derivation for Other Physical Variables

(1) Fundamental Assumption

a. The deformation model of the lining rings is assumed to be as horizontal ellipse;

b. Six segments of each lining ring are assumed to be the rigid body. The deformation of lining rings is mainly the opening length of the bolts connecting longitudinal seams, whereas the deformation of the segments is very small due to the large stiffness.

Based on the assumptions above, the lining ring can be seen as a system composed of six rigid bodys with one degree of freedom.

(4) Formula Derivation

As shown in figure 5, there are geometrical relationships as follows:

$$b\cos\alpha + \frac{a}{2} - \frac{d}{2} = c\cos\beta \tag{1}$$

$$D\sin 73^o = a + 2b\cos\alpha \tag{2}$$

Where, a, b, c, d are the linear distance between the adjacent longitudinal connecting seams respectively, and α, β are the angle of line a, b and the horizontal axis respectively, D is the horizontal diameter of the lining ring, as shown in figure 3.

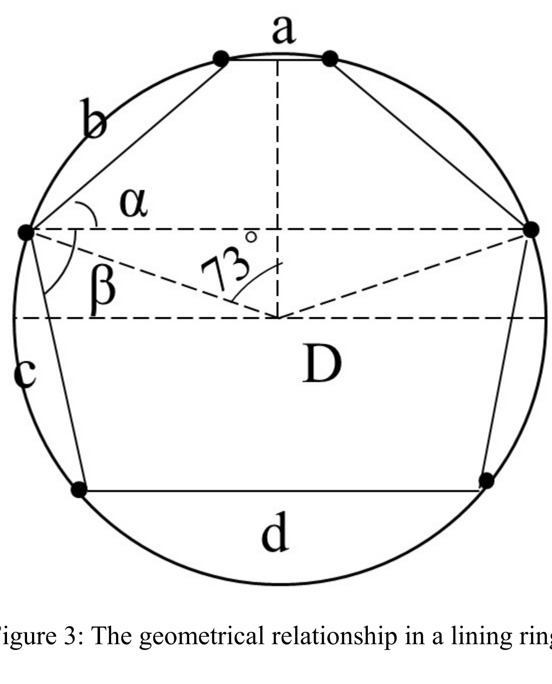

Figure 3: The geometrical relationship in a lining ring

Differentiating Equation (2), we can get the relationship between the variation of horizontal diameter and the inclination variation of adjacent block:

$$dD = \frac{-2b\sin\alpha}{\sin 73^{o}} d\alpha \tag{3}$$

Differentiating Equation (1), we can obtain the relationship between the inclination variation of standard block and that of adjacent block:

$$d\beta = \frac{b\sin\alpha}{\sqrt{c^2 - \left(b\cos\alpha + \frac{a-d}{2}\right)^2}} d\alpha \tag{4}$$

The opening length of longitudinal connecting seam at joint No.2 equals to the sum of the inclination variation of standard block and that of adjacent block:

$$d\theta = d\alpha + d\beta = \left(1 + \frac{b\sin\alpha}{\sqrt{c^2 - \left(b\cos\alpha + \frac{a-d}{2}\right)^2}}\right) d\alpha \tag{5}$$

The evolution of tunnel transverse deformation with loading above tunnel is studied using numerical simulation considering the effect of the elastic resistance of surrounding soil and lateral coefficient of earth pressure, with the depth range of tunnel 0~6m; with the corresponding vertical loading 0~1098kPa; with the lateral coefficient of earth pressure 0.5, 0.6, 0.7, 0.8; with the resistance coefficient of earth pressure 625kPa/m, 1250kPa/m, 2500kPa/m, 5000kPa/m, 10000kPa/m, which is usually less than $10^4\ kPa/m$. In this paper, combining the loading, the lateral coefficient and the resistance coefficient of earth pressure, 21 kinds of working conditions are conducted. Then we get two equations as follows.

The relationship between the concrete stress of bolt and the variation of horizontal diameter can be described as:

$$\sigma_b = \begin{cases} 11.84dD + 74.05, & x \le 47.8 \\ 4.15dD + 441.86, & 47.8 < x \le 86.4 \\ 800, & x > 86.4 \end{cases} \tag{6}$$

where σ_b is the stress of concrete of bolt.

The relationship between the stress of concrete of joint and the variation of horizontal diameter can be described as:

$$\sigma_c = \begin{cases} 0.883dD + 0.303, & x \le 28.3 \\ 0.122dD + 21.80, & 47.8 < x \le 86.4 \end{cases} \tag{7}$$

Where σ_c is the maximum stress of concrete at joint No.2.

1.4. The Warning Threshold Value in terms of Inclination Variation

In order to ensure the safety at in-service stage, general requirements of metro shield tunnel in Shanghai are as follows:

a. The cumulative deformation of diameter is less than 5‰D;
b. To avoid leakage, the circular connecting seam should be less than 6mm;
c. The stress of bolt is less than the yield strength;
d. The stress of segment concrete should be less than the compressive strength.

On the basis of the analysis above, we can set the warning threshold value of different grades in terms of inclination variation, as shown in table 2.

Table 2: threshold value of different grades in terms of inclination variation

Warning Grade	The range of Inclination Variation($10^{-4}\,rad$)	Warning State	Acceptable Criterion
No Warning	<36.3	/	Negligible
Level 4	36.6~56.0	The variation of horizontal diameter reaches 5‰D.	Tolerable
Level 3	56.0~70.3	The bolt reaches the yield strength.	Acceptable
Level 2	70.3~97.7	The joint waterproof device fails.	Unacceptable
Level 1	>97.7	Concrete is crushed.	Impermissible

2. THE REAL-TIME MONITORING SYSTEM BASED ON INTERNET OF THINGS

Shanghai metro line 12 which is under construction is a south-north line. The monitoring section is between South Shanxi Road and West Nanjing Road and characterized by densely surrounding buildings and complex geological environment. A real-time monitoring system based on the internet of things is implemented to ensure the safety of the operation of this interval tunnel.

2.1 SYSTEM ARCHITECTURE

The real-time monitoring system based on the internet of things is composed of three layers, which are: the data acquisition layer, the data transmission layer and the data processing and application layer as shown in figure 4.

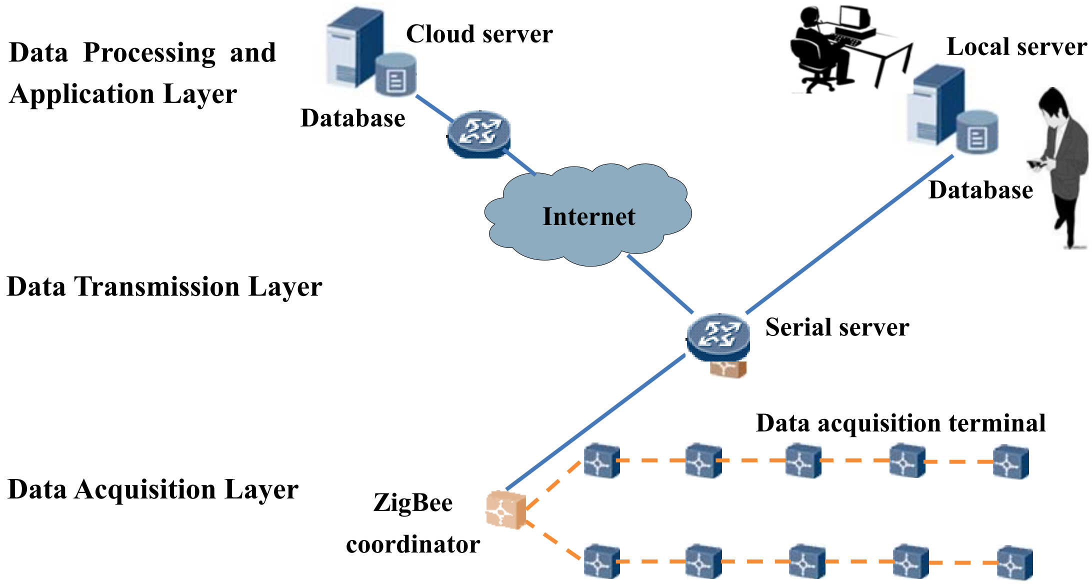

Figure 4: The main structure of the real-time monitoring system for metro tunnel

The data acquisition layer is the basis of the system, and contains wireless inclinometers with high precision to measure the variation of inclination of selected lining segments. There are 250 monitoring cross sections when deploy inclinometers on every other ling ring, including 20 cross sections each deployed with four inclinometers and 230 cross sections each deployed with one inclinometer. The information acquired by inclinometers are stored in the data collection terminals of the data acquisition layer.

The data transmission layer is a significant link that connects the data acquisition layer and the data processing and application layer. This layer adopts ZigBee wireless network to transmit the field measurement data to the remote computers, cloud servers and database servers.

The data processing and application layer utilizes Shanghai mobile company server platform to store and view the monitoring data, make graphical analysis, and set warning values. This layer both analyzes all collected information and indicates the current conditions of structures scientifically and effectively at all times. Therefore, the management team can conduct effective countermeasures as needed rather than waiting for an accident to happen.

3. WAY FORWARD

Implementing the real-time monitoring system contributes to the safe operation and long-term maintenance of the tunnel structure, and provides a valid way to forecast the occurrence of catastrophic events and reduce the maintenance cost.

The establishment of real-time monitoring system will potentially provide the knowledge and reference for similar projects, and enable accident prevention move from reactive maintenance to proactive management.

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