SIMPLE MECHANICAL METHODS FOR MONITORING AND DATA-VISUALIZATION DURING NATM TUNNEL CONSTRUCTION

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It is a common view that monitoring of tunnel construction performance allows for an evaluation of the engineering safety. However, some accidents still could not be eliminated, such as the collapse of the tunnel face, which urgently requires improvement of the monitoring techniques. This paper introduces some simple methods for not only the measurement of deformation of ground adjacent to the tunnel face, the convergence displacement, axial force of the rock bolts, but also simultaneous visualization of the performance in a mechanical way. In addition, the basic concept of the new methodology in visualization without using electricity is presented, as well as its applicability in engineering.

Key Words: *NATM tunnel, monitoring, On Site Visualization, simple mechanical methods*

1. INTRODUCTION

The measurement work of the NATM tunnel construction is a systematic one, including tunnel face monitoring, convergence displacement measurement, axial force of rock bolts and so on. Based on these measurement results, an approximate and comprehensive evaluation of the construction is possible to be obtained. It also plays an important part in back analysis and design-improving work.

However, it is difficult to carry out a perfect measurement for mountain tunnel construction because there are more or less some shortcomings of the existing sensors, such as the disruption of the procedure of constructions. Sometimes the high cost of the monitoring is another problem in consideration. In addition, when an unexpected displacement happens during construction, it requires sending out the warnings or signals to the workers to withdraw from the field immediately.

Considering these described above, a new concept of “On Site Visualization” has been proposed to monitor the deformation and to visualize the measurement results on real-time by different color of light. It is capable of not only sensing data, but visually outputting the measurement result simultaneously by different colors of light or signs for workers in the field and all concerned[1)]. Based on this concept, a series of sensors have been developed and applied for monitoring in field at a low cost and with low power consumption in Japan and abroad since 2007. It is evident that this new scheme helps improve the safety management practice.

In this paper, some new methods for monitoring the displacement during tunnel construction, such as tunnel face monitoring, convergence displacement measurement are described conceptually. In addition, an improved method for measuring the axial force of the rock bolts is introduced. Most of the simple methods are performed mechanically, without using electricity. At last, the accuracy and applicability of these simple methods is discussed briefly.

2. TUNNEL FACE MONITORING

The stability of tunnel face has major effect on the safety of excavation of tunnel in unfavorable rock mass. Therefore, it is necessary to monitor the movement of ground ahead of tunnel face and tunnel face itself during tunneling.

Here a new technique is developed to monitor and visualize the movement of ground on real-time using optical fibers as shown in **Figure 1**. It is mainly consisted of a color filter sheet within four different colors, a sliding stopper for detecting the deformation of ground, and a plastic optical fiber to transmit light, where there is a gap to allow the color filter to pass through. White light travels along the optical fiber, as it passes through the color filter, its color changes same as the color of filter and it can keep on traveling along the next optical fiber and emit at the end of the fiber. It follows the optical principle that the color filter sheet would have to absorb some other wavelengths of visible light while transmitting the color of light same as filter itself. For example, the red filter can only transmit the red color of light. So if the ground deformations happen, the sliding stopper shall move simultaneously together with the color filter, the color of light changes at the same time, which can be seen easily at the end of optical fiber by workers in the field. Thus, the monitoring of ground movement can be achieved.

It should be noted that the band widths of different colors are determined according to the safety management. A general monitoring process is illustrated in **Figure 2**. The sensor begins to work after it is installed inside the borehole by grouting ahead of the tunnel face. It is very useful that the sensor could continue to monitor the movement of ground even if the part exposed outside the tunnel face is cut as needed[2].

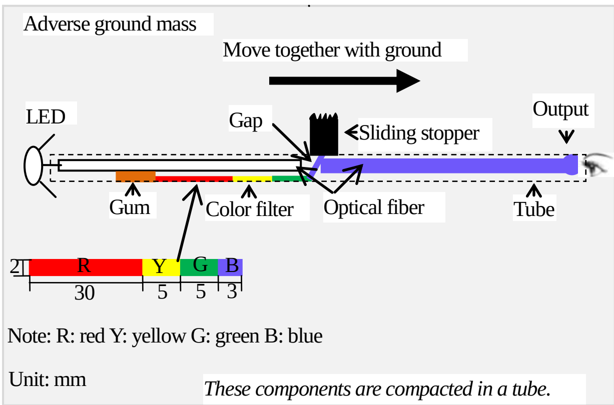


Figure 1 Layout of Ground Deformeter.

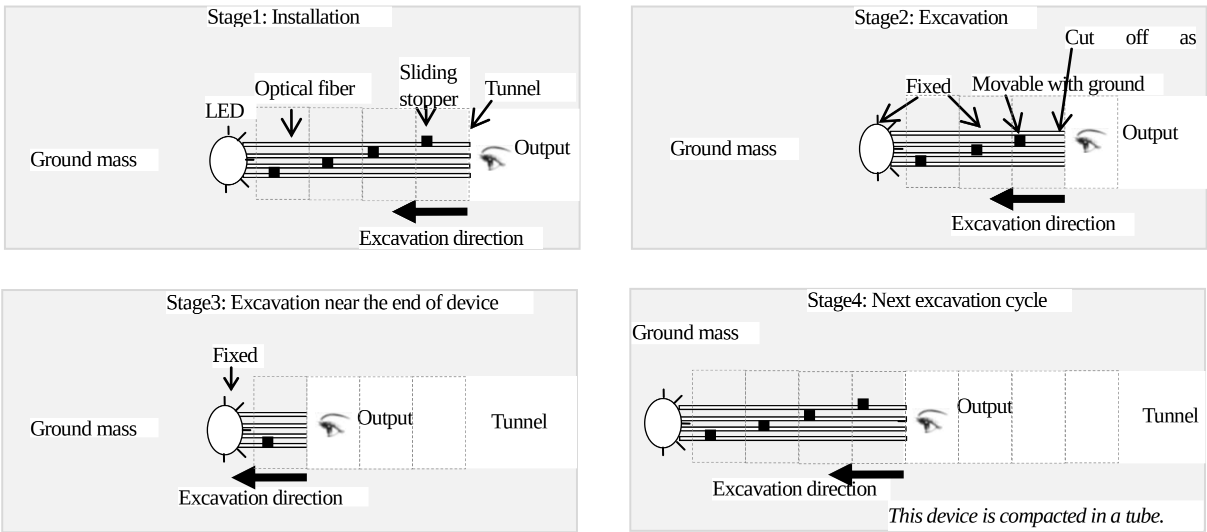


Figure 2 Procedure of monitoring by Ground Deformeter.

3. CONVERGENCE MONITORING

A conventional method for convergence measurement is to utilize convergence tape to obtain a deformation profile e.g. with 3 pins, which is helpful for back analysis. The sectional deformation of tunnel could be judged both primarily and qualitatively by the change of the shape of the triangular profile. Now we provide two methods for monitoring the displacement of point at the ceiling and the relative displacement between two measuring points on the periphery of tunnel respectively.

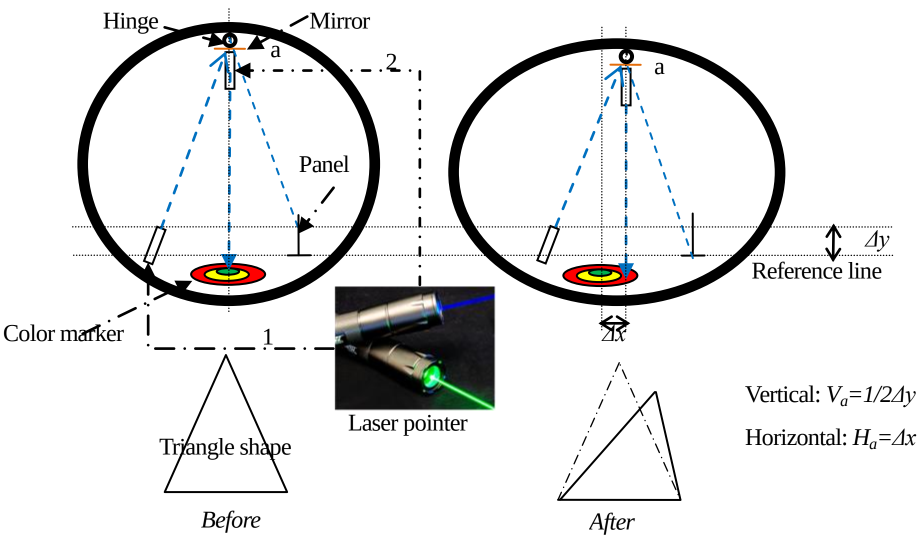


Figure 3 Convergence measurement of the point at the roof.

(1) Movement of the point at the ceiling

In practice, the point at the crown of the tunnel near the face is most likely to move as the excavation of tunnel advances. To some extent it is the key point in convergence measurement. Thus, if we get to be aware of the movement of this point, a primary judgement of the deformation of tunnel could be done. However, it is not easy to measure its movement directly during construction. In order to measure the vertical and horizontal displacement of the point at the roof, an approach is proposed using laser pointer and mirror as shown in **Figure 3**.

For vertical displacement monitoring, a mirror is set up at the point at the roof, within a hinge connecting the mirror and the pin, which keeps the mirror horizontally. Note that the laser pointer 1 and the ruler panel remain stable during measurement. The laser is reflected from mirror and projected on the panel. When the point at the roof settles, the vertical displacement V_a can be expressed as

$$V_a = 1/2 \Delta y \quad (1a)$$

where Δy is the relative displacement value of the light projection read from the panel.

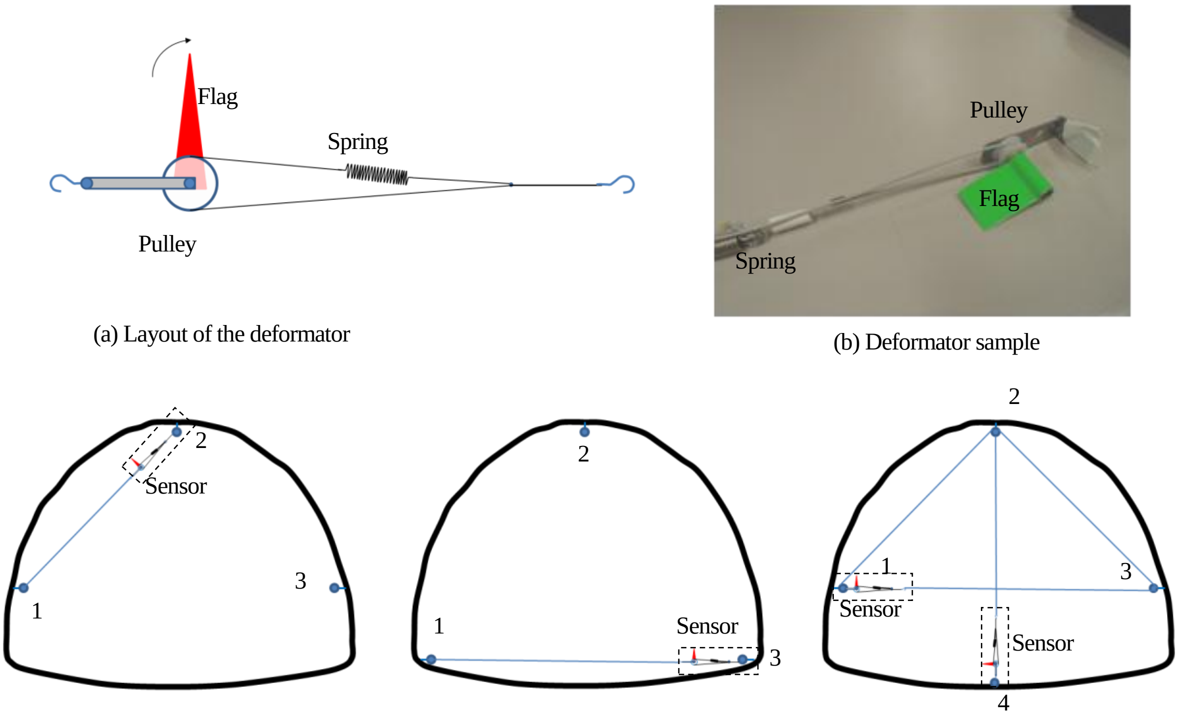
For horizontal displacement monitoring, same as the installation of mirror, a laser pointer 2 is set up together with the mirror. There is also a hinge between the laser pointer 2 and the pin so as that the laser pointer can stay vertically. When the measuring point moves, its horizontal displacement can be read directly from the panel on the ground and therefore we have

$$H_a = \Delta x \quad (1b)$$

where H_a is the horizontal displacement of the point at the roof and Δx is the displacement value of the projection on the panel. The displacement value on the panel can be designed with different colors at intervals, such as blue, yellow, red and so on. By doing this, the monitoring of the convergence can be done on real time visually by the workers in the field.

(2) Relative displacement

The deformation sensor is a device which can measure the relative displacement between two points and show the result by the rotation of the indicator like a flag. As shown in **Figures 4(a)** and **4(b)**, the sensor consists of the pulley, a spring, and the stainless wire. The flag is attached to the pulley, which rotates together with the pulley. When a relative displacement happens, the spring is to be elongated or contracted, thus the pulley is rotated by the wire together with the flag. Therefore, the monitoring of the displacement is obtained by the identification of rotation of flag. The precision of the sensor is determined by the diameter of the pulley. This sensor can be used in the measurement of the triangular convergence displacement even if in the condition that there is no power supply. The measurement is able to be



(a) Layout of the deformator

(b) Deformator sample

(c) Two inclined points

(d) Two points on horizontal

(e) Three points measurement and two points on vertical

Figure 4 Relative displacement sensor and its application.

employed in different way such as the inclined points or the horizontal points, as shown in **Figures 4(c)**, **4(d)** and **4(e)**.

With the help of the measurement of the movement of the point at the ceiling combined with the relative displacement of the tunnel periphery, an overall assessment of the tunnel structure can be concluded, such the triangle shape change as shown in **Figure 3**, which gives a base of the safety management of the construction. The back-analysis method is often used in tunnel engineering in terms of the measurement of the tunnel convergence. However, the relation between the tunnel convergence and the state of stress of tunnel has not been clarified yet until now. A further study focus on this should be carried out if possible.

4. AXIAL FORCE OF ROCK BOLT MEASUREMENT

It is known that the distance between the plate and the fixed zone changes according to fluctuation of the load of the bolt, which means there is a linear relationship between the change of distance and axial force of rock bolt. Bases on this, some methods have been introduced in literature such as the light emitting deformation sensor for the axial force of rock bolt measurement (S. Akutagawa, et al. 2013)[3]. It makes use of a spring to grasp the axial force of the anchor bolt by translating the load to the elastic deformation with the help of a stiff wire. This is an innovative design because it provides an indirect way to measure the force instead of measuring the axial force of bolt directly.

Now an improved method is introduced in **Figure 5**. A cylinder with a flag is set up upon the plate, which can be rotated around with the thread twining it. The stiff wire remains in the ground, connected with a thread which twines the cylinder outside the ground, then a spring, and last fixed on the plate. The spring is used to adjust the tension of the whole line. Therefore, when the load of bolt changes, the length of the line (composed of wire, thread and spring) elongates or contracts accordingly, initiating the flag to rotate. Thus, the monitoring and visualization of axial force of rock bolt can be achieved mechanically. Note that there is no electricity used for this sensor.

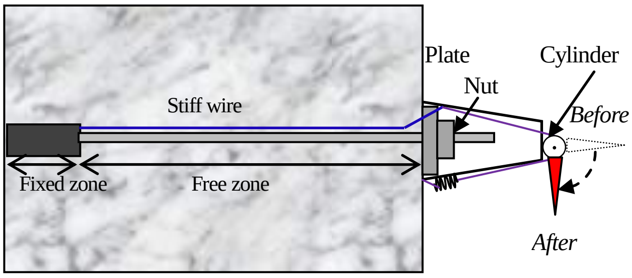


Figure 5 Axial force measurement for rock bolts.

5. DISCUSSIONS AND CONCLUSIONS

The effective monitoring of tunneling means a lot not only to the safety management of tunnel constructions, but to the improvement of numerical and theoretical analysis in tunnel engineering. This requires the development of the measurement techniques. Some methods based on the "On Site Visualization" are presented to monitor and visualize the deformation of the ground ahead of tunnel face, the convergence displacement, and the axial force of rock bolts, which covers the main objectives of the conventional measurement in tunneling. These techniques perform in a simple way mechanically. The underlying idea of these methods is very interesting. Taking the convergence measurement for example, the linear displacement is to be translated to the rotation behavior of the indicators. This kind of indirect measurement method shall be widely used in the future monitoring techniques.

The data-visualization can be carried out in different ways, such as the color of light, the color plate and some other indicators. On one hand, the OSV technique transmits the information of measurement results to the concerned people directly, which saves time compared with the conventional monitoring methods. On the other hand, because it is difficult for people to judge a very small movement of the indicator by their naked eyes, the accuracy of these techniques is more or less affected. Generally, the displacement could be measured and visualized in millimeter level. As for the Ground Deformeter for tunnel face monitoring, since the diameter of the testing optical fiber is 1mm, the smallest displacement would be detected by 1mm according to the change of the colors of light. Some improvement could be made to overcome these problems. For example, the complex gear system is used to change the ratio of the displacement value of the objects and movement value of indicators so that a higher accuracy of monitoring can be obtained.

The simple methods without using electricity make it possible to monitor the tunneling construction even in a crucial circumstance on real-time. The experiment for applicability of these methods should continue to be done. Since there are no complex electric instruments used, the cost of these methods would be low. Therefore, many more sections could be monitored as needed within a confined budget, which enhances the safety management for construction.

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トンネル工事における簡易モニタリングとデータの可視化手法

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山岳トンネルの施工で通常実施される様々な計測は施工の安全性を確保するためには欠かせないものとなっている．しかしながら，切羽周辺の土砂崩落の事例はいまだに起こり続けており，計測の更なるコストダウンと合理化が望まれている．本報告では，トンネル切羽周辺地山の変位、内空変位、ロックボルト軸力などを低コストで計測するだけでなく，その状態（変位の大きさなど）を簡易な装置を用いてリアルタイムに可視化し，危険の察知と適切な対処を可能とするような新しい方法論について紹介する．これまで，電気を使用する様々なセンサを用いた方法論によるデータの可視化については例があるが，本篇では電気を用いないシンプルな方法論の基本的概念を紹介し，その可能性について議論する．