Deflection detection of the cement stabilizing layer based on the falling ball test method

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Abstract. The detection of the deformation characteristics of geotechnical materials is very important for improving the safety of highways. With the improvement of the detection technology, the falling ball test (FBT) method has been gradually applied to measure mechanical properties of the geomaterials. In order to determine the reliability and the stability of the FBT method, the results of using the FBT method to detect the deflection value of the cement stabilizing layer are compared in this paper with the results of using a falling weight deflectometer (FWD), which is recognized worldwide as an ideal non-destructive detection equipment for the road mechanical performance. It is found that FBT method has high stability and reliability during the test.

1. Introduction

In recent years, with the rapid development of high-speed railways and highways, it is particularly important to control the quality of subgrade to ensure the safety of transportation. The mechanical properties of geomaterials are a crucial criterion for evaluating the quality of subgrade. It is of great significance to improve the durability of the subgrade by the effective detection for the deformation characteristics of geomaterials and increasing the overall uniformity of the subgrade[1-2].

The testing methods for the quality of subgrade filling engineering mainly include bearing plate method, Benkelman beam deflectometer method, field CBR method, falling weight deflectometer (FWD) method, and so on. These methods may require using a test vehicle, or require a motor tractor to pull the test equipment into position, or are inefficient and destructive. Meanwhile, these methods are more complicated to operate and have high technical requirements. In addition, the portable falling weight deflectometer (PFWD) is also an important testing method to evaluate the quality of roadbed because of its small size and portability. However, this method has limitations in terms of accuracy and applicable scope.

The falling ball test (FBT) technology, which was proposed jointly by Wu Jiaye and researchers in Japan[3], is non-destructive and can quickly and accurately detect the deformation characteristics of geomaterials. Since 1999, the FBT technology has been promoted gradually and applied in more than 300 domestic and foreign projects, as shown in figure 1.

Therefore, the FBT technology is used in this paper to detect the deflection value of the cement stabilizing layer. Results are compared with the test performed by a falling weight deflectometer (FWD) to validate the reliability and the stability of the FBT method.
2. Principles of the deflection detection using FBT

The falling ball test (FBT) technology, which is derived from the elastic contact theory proposed by Hertz in 1881\cite{4-6}, can directly measure the deformation modulus $E$ and the modulus of resilience $E_r$ of geomaterials. Then, according to the elastic theory and related empirical formulas, the Beckman deflection value $L$ can be calculated.

In the light of the elastic contact theory, when a sphere with known rigidity collides with an object with unknown rigidity, the greater the rigidity of the object will lead to the shorter the contact time ($T_c$) during the collision, as shown in figure 2 below.

\begin{align}
E &= \frac{(1 - \mu^2_e) \cdot m_E_1}{0.0719E_1 \cdot (Rv_0)^{1/2} \cdot T_c^{1/2} - m_1 \cdot [1 - \mu^2_e]} \\

\text{where } &E, \mu, m \text{ and } R \text{ are deformation modulus, Poisson's ratio, mass and radius, respectively. Subscripts 1 and 2 denote the falling ball with known rigidity and materials need to be tested. } v_0 = \sqrt{2gh} \text{ is the contact velocity and } H \text{ is the height of the falling ball.}
\end{align}

However, Hertz elastic contact theory is only applicable to linear elastic materials, while geomaterials are typical elastoplastic materials. Therefore, equation (1) need to be revised to apply to geomaterials.

As shown in figure 3, the collision process of the falling ball and geomaterials can be divided into two parts, namely the compression part and the rebound part. The deformation modulus $E$ is calculated by the contact time $T_c$ of the compressed part, and the modulus of resilience $E_r$ is obtained by the contact time $T_r$ of the rebound part.

So, the deformation modulus $E$ can be calculated as follows:

\begin{align}
E &= \frac{\kappa \cdot (1 - \mu^2_e) \cdot m_E_1}{0.0719E_1 \cdot (Rv_0)^{1/2} \cdot T_r^{1/2} - m_1 \cdot [1 - \mu^2_e]} \\

\text{where } \kappa &	ext{ is a parameter related to the materials and the test conditions.}
\end{align}
where $\kappa$ is a correction factor. 

And the modulus of resilience $E_{ur}$ can be calculated as follows:

$$E_{ur} = \frac{\kappa \left(1 - \mu^2_i\right) \cdot m_i E_i}{0.0719 \cdot \left(R V_i\right)^{m_i} \cdot \left(1 - \mu^2_i\right)}$$

(3)

According to the modulus of resilience $E_{ur}$, the Beckman deflection value $L$ can be calculated in the light of empirical formula:

$$L = \frac{2p\delta}{E_{ur} \times 0.01 \text{mm}} \left(1 - \mu^2_i\right) a$$

where $p$ is the average vertical loads of the testing wheel, $\delta$ denotes the radius of equivalent circle, $\mu$ is the Poisson's ratio of the subgrade and $a$ is a constant coefficient equals to 0.712.

However, when using the FBT technology to calculate the deflection $L$, the influence of depth cannot be ignored. So, we revised the equation (4) to make it suitable for the deflection detection of the FBT technology:

$$L = \frac{2p\delta}{E_{ur} \times 0.01 \text{mm}} \left(1 - \mu^2_i\right) a\eta_1\eta_2$$

(5)

where $\eta_1 = 1.5$ denotes the empirical correction factor and $\eta_2 = 0.8 \sim 1.3$ is the stratification correction factor.

3. Experiments of the deflection detection using FBT

This section shows the results of the deflection detection using the falling ball test (FBT) technology. In order to verify the reliability and the stability of the FBT method, results are compared with the deflection tested by the falling weight deflectometer (FWD).

3.1 FBT tester

The FBT tester shown in figure 4 below is used in this paper to test the modulus of resilience of the cement stabilizing layer in order to deduce the Beckman deflection value. And the actual operation process of the FBT tester is shown in figure 5.

The test process of the FBT tester is shown below:

1) lift the ball to a certain height (standard height is 0.5m);
2) the ball falls freely and collides with geomaterials to be tested, the acceleration of the falling ball is measured during this process;
3) through the analysis of the acceleration, mechanical properties of geomaterials can be obtained.

The test process of this type of FBT tester is very simple, just lift the ball to a certain height and fall freely. There is no need to level the test site, nor to deliberately select the test location, and the test time for each measuring point is less than 3 minutes. Furthermore, this type of FBT tester is applicable for a wide range of materials and the test results are stable and objective.
3.2 Experimental results

The test site chosen in this paper is the upper base layer of 5% cement stabilizing layer of a road section with a length of about 400m and a width of 10m, as shown in figure 6. In this road section, 37 measuring points are arranged longitudinally with an interval of 10m, of which measuring points No.1-18 are for ordinary cement stabilizing layer, and measuring points No.19-37 are for oiled cement stabilizing layer.

![Figure 6. Test site](image)

To detection the deflection value of 37 measuring points in this road section, the FBT tester is used to test the resilience modulus to calculate the deflection value. In order to verify the stability of the FBT technology, the FWD is also used to test the deflection and the results are compared with the deflection obtained by the FBT. Then, a road roller is used to roll the road section. The purpose is to generate microcracks in the cement stabilizing layer to reduce its modulus. Continue to use the FBT and FWD separately to test the road section after rolling to further validate the stability and reliability of the FBT technology.

3.2.1. Experimental results of the FWD.

Deflection values tested by the FWD for the ordinary and oiled cement stabilizing layers before and after rolling are shown in figure 7 and figure 8.

![Figure 7. Deflection values tested by the FWD for the ordinary cement stabilizing layer](image)
![Figure 8. Deflection values tested by the FWD for the oiled cement stabilizing layer](image)

As shown in figure 7 and figure 8, because of rolling the road section, the modulus decreases, so there are 16 deflection values of the ordinary cement stabilizing layer and the oiled cement stabilizing layer increasing respectively after rolling.
3.2.2. Experimental results of the FBT.

Deflection values calculated by the modulus of resilience measured by the FWD for the ordinary and oiled cement stabilizing layers before and after rolling are shown in figure 9 and figure 10.

![Figure 9. Deflection values calculated by the FBT for the ordinary cement stabilizing layer](image1)

![Figure 10. Deflection values calculated by the FBT for the oiled cement stabilizing layer](image2)

Deflection values calculated by the FBT in figure 9 and figure 10 show good correlations between results before and after rolling.

3.2.3. Analysis of experimental results.

In order to show clearly the comparative results between FWD and FBT before and after rolling, experimental results are combined in the following figure 11.

![Figure 11. Comparative results](image3)

It can be seen from the above figure 11 that deflection values measured by the FWD are all greater than those obtained by the FBT method. Meanwhile, values obtained by the FWD increase significantly after rolling, while the change in the deflection values calculated by the FBT is not obvious. So, there is a large dispersion when using the FWD to test the deflection after rolling, but using the FBT shows a better correlation before and after rolling.
The regression analysis results of deflection values detected by FBT before and after rolling for oiled cement stabilizing layer are shown in figure 12, and the regression correlation coefficient $R^2=0.8298$.

The reason for the clear difference between deflection values obtained by the FBT and FWD is that the test effective depth of these two method are different, as shown in Figure 13.

The effective depth of the FWD is deeper, so measuring results are easily affected by the lower base layer beneath the upper layer of the cement stabilizing layer and the interface between them. According to the experimental results, deflection values measured by the FWD increase obviously because the interface is disturbed by the rolling so that the overall deflection increases.

However, the effective depth of the FBT in the cement stabilizing layer is about 10cm, so the deflection values measured by the FBT are not affected by the lower base layer and the interface. Therefore, deflection values tested before and after rolling do not change much and have a good correlation.

In conclusion, in the process of measuring mechanical properties of the cement stabilizing layer, the results obtained by using the FBT method are more stable and have a better reliability than using the FWD.

4. Conclusion
In the present study, the FWD and the FBT technology are used respectively to measure the deflection values of the cement stabilizing layer of a road section, and it is concluded that using the FBT method has better stability and reliability in this process.

In future work, we will take samples of the cement stabilizing layer before and after rolling, and the material strength test is going to be used to validate the changes of the cement stabilizing layer itself, thereby further verifying the detection accuracy of the FBT technology.

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