Comparative Test and Analysis of Falling-Ball Instrument and FWD Deflection Detection Method

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Abstract. Through the experiment, the deflection detection methods of the falling-ball instrument and the falling weight deflect meter (FWD) were compared, and their correlations were analyzed. The results show that the test depth and range of FWD are larger than the falling-ball instrument, and there is a good linear relationship between the road surface deflection values measured by the falling-ball instrument and FWD.

1. Introduction
With the rapid development of China's economy and society, the scale of highway construction is gradually increasing. It is particularly important to effectively control the quality of subgrade engineering and ensure the safety and comfort of driving. Due to the complexity and diversity of subgrade packing, uneven settlement often occurs after rolling, which affects the quality of the project and causes certain economic and social losses. Therefore, effective deflection detection is of great significance to increase the overall uniformity of the subgrade and improve the durability of the subgrade. 

Deflection detection methods mainly include the traditional manual deflection detection methods and continuous deflection detection methods. The prescribed methods in Field Test Methods of Highway Subgrade and Pavement (JTG 3450-2019) [1] are Beckman beam method, falling-ball instrument, and falling weight deflect meter (FWD). Laser deflection instrument, roller deflection instrument (RWD) are new generation of deflection detection equipment based on laser technology. In order to effectively improve the efficiency and quality control level of the on-site detection during the road construction process, this paper compares the deflection detection methods of the falling-ball instrument and FWD through experiments, and analyses their correlations. The test results can provide a reference for the engineering applications.

2. Deflection detection methods of the falling-ball instrument and FWD
Deflection refers to the vertical deformation of the subgrade or road surface under load action, which can be restored after unloading. The rebound deflection of the pavement can not only reflect the overall rigidity and strength of the subgrade pavement structure, but also have a certain internal relationship with the use state of the pavement. Generally, the larger the rebound deflection value is, the greater the plastic deformation of the pavement structure is, and thus the poorer the fatigue resistance is. Otherwise, the pavement structure has better fatigue resistance and can withstand larger traffic.
2.1. Falling-ball instrument
The detection methods of the falling-ball instrument can directly measure the deformation modulus $E$ and rebound modulus $E_{ur}$ of the material by using Hertz collision theory and the plastic correction of geotechnical materials through falling a metal rigid sphere. Based on the elastic theory and empirical formula, the formula can also calculate the bed coefficient $K_{30}$ (also called foundation coefficient), Beckman deflection $L$ and physical indicators (such as dry density, compaction, and relative density).

The detection methods of the falling-ball instrument can be used to quickly determine the rebound modulus of clay, silt, sandstone subgrade. The maximum particle size of the test material should be less than 10cm and the test depth should not be greater than 25cm. In order to verify the accuracy and stability of the falling-ball instrument, it will be compared with FWD.

2.2. FWD
In recent years, the FWD method has been used to measure the dynamic deflection of the pavement and back calculate the rebound modulus, which has become an important method for evaluating the structural condition of the pavement. The detection methods of FWD measures the instantaneous deformation of the subgrade or pavement under the impact load of a certain height dropped by a heavy hammer of standard quality, that is to measure dynamic deflection and deflection basin under dynamic load.

When using this method, experimenters drive the test car to the test location, and start the drop hammer device through the hydraulic system under computer control, so that the drop hammer of a certain mass can freely fall from a certain height. The impact force generated by falling hammer acts on the bearing plate and is transmitted to the pavement, resulting in road surface deflection. The sensors distributed at different distances from the measuring point detect the deformation of the surface of the structural layer, and by computer record the signals, which are the deflection and deflection basin of the pavement in measuring point.

3. Comparative experiment

3.1. Overview
In order to compare the test results of the falling-ball-type rebound modulus tester and the vehicle-mounted FWD subgrade deflection, a comparative experiment of deflection and rebound modulus was carried out.

We adopt a sphere with a mass of 19.1Kg as the falling ball and the free fall height is taken as 50cm. Since the drop weight load disk is 30cm, which is larger than the diameter of the falling ball, the falling ball test is a circular area with a diameter of 60 cm. The center point is tested once, facing the direction of the large mileage, and the left, top, right, and bottom points 40cm away from the center point are tested in sequence. The point distance of 40cm is chosen to avoid the influence between points, as shown in Fig. 1.

![Figure 1. Layout of falling-ball](image-url)
In the drop weight test, we adopt the standard specified force value of 50KN and take 9 deflection sensors. Only the deflection value in the center point is used. During the test, a hammer is pre-hit at the center of the circle, and then the two hammers are tested with 50KN. When calculating, the average value of the two hammers is taken as the deflection at this point.

Due to the large value of test force from the drop weight, it will have a compacting effect on the subgrade after the test. Therefore, the ball drop test is performed first, and then the drop weight test is performed at the same point. A total of 40 continuous areas were tested, whose mean of deflection will be fitted and compared with the deflection at the center point.

3.2. Test data

The falling-ball test data in the first area are shown in Figs. 2 and 3. It can be seen that due to the difference in the uniformity of the subgrade, some deflection values in the same area are quite different.

| Test times | Measure acceleration Ch. | ACC(m/s²) | Test TC(ms) | Fix TC(ms) | Contact diameter(m) | Maximum settlement(m) | Maximum impact force(KN) | Deformation modulus(MPa/m) | CBR | Rebound modulus(MPa) | K30(MPa) | Deflect(0.01mm) |
|------------|---------------------------|-----------|-------------|------------|---------------------|------------------------|----------------------------|----------------------------|-----|---------------------|----------|-----------------|
| 1          |                           |           |             |            | 0.063               | 0.004                  | 93.33                      | 62.12                      | 298.70 | 78.74               | 51.42    | 171.00          |
| 2          |                           |           |             |            | 0.063               | 0.004                  | 104.52                     | 84.74                       | 369.19 | 92.86               | 64.49    | 138.64          |
| 3          |                           |           |             |            | 0.063               | 0.004                  | 104.52                     | 92.86                       | 324.85 | 156.05              | 56.27    | 156.05          |
| 4          |                           |           |             |            | 0.063               | 0.004                  | 110.03                     | 110.03                      | 444.85 | 131.70              | 78.53    | 131.70          |
| 5          |                           |           |             |            | 0.063               | 0.004                  | 92.17                      | 92.17                       | 310.39 | 157.22              | 53.59    | 157.22          |
| average    |                           |           |             |            |                     |                        |                            |                             | 349.60 | 150.92              | 60.86    | 150.92          |
| Standard deviation |       |           |             |            |                     |                        |                            |                             | 12.39 | 15.73               | 11.05    | 15.73           |
| Equivalent value |             |           |             |            |                     |                        |                            |                             | 71.2  | 96.01               | 59.52    | 96.01           |

Figure 2. Waveform data of falling-ball waveform data.

Figure 3. The falling-ball test data in the first area.

The drop weight test data at the center point are shown in Table 1.
Table 1. Deflection values at the center point of drop hammer

| Test point | Measured deflection value (0.01mm) | Test point | Measured deflection value (0.01mm) |
|------------|-----------------------------------|------------|-----------------------------------|
|            | Second hammer | Third hammer | Second hammer | Third hammer |
| 1          | 183.35        | 170.76      | 21         | 129.31        | 129.61      |
| 2          | 143.08        | 139.58      | 22         | 82.98         | 84.91       |
| 3          | 174.61        | 164.22      | 23         | 109.64        | 110.61      |
| 4          | 136.56        | 132.99      | 24         | 161.83        | 154.71      |
| 5          | 166.18        | 155.01      | 25         | 173.52        | 154.25      |
| 6          | 155.79        | 149.82      | 26         | 158.69        | 148.25      |
| 7          | 149.03        | 144.04      | 27         | 143.48        | 137.14      |
| 8          | 168.19        | 156.66      | 28         | 194.61        | 177.93      |
| 9          | 135.36        | 129.69      | 29         | 209.65        | 189.37      |
| 10         | 120.63        | 118.21      | 30         | 207.27        | 197.48      |
| 11         | 152.15        | 146.54      | 31         | 172.71        | 154.77      |
| 12         | 185.37        | 177.90      | 32         | 169.54        | 153.08      |
| 13         | 194.57        | 180.43      | 33         | 149.40        | 140.96      |
| 14         | 201.62        | 184.35      | 34         | 161.61        | 149.64      |
| 15         | 116.94        | 117.21      | 35         | 153.88        | 140.60      |
| 16         | 124.08        | 123.23      | 36         | 147.75        | 136.58      |
| 17         | 114.06        | 114.69      | 37         | 161.66        | 151.06      |
| 18         | 77.22         | 78.57       | 38         | 139.28        | 135.39      |
| 19         | 122.64        | 118.45      | 39         | 127.37        | 123.29      |
| 20         | 129.62        | 128.06      | 40         | 135.68        | 129.75      |

3.3. Results statistics and analysis

1) The statistics of deflection values

   The statistics of deflection values at the center point from two detection methods are shown in Table 2. The deviation is due to the following reasons.

   The diameters of the bearing plate and sphere have a difference. The diameter of the drop weight is 30 cm and that of the falling-ball is 19 cm, where the difference is about 11 cm. The subgrade is made of uneven material and thus the tested area is different.

   The test depths have a difference. Due to the large difference in drop quality, the test depth of the drop weight is large. Because the road bed structure is divided into multiple layers, the drop weight test is a multi-layer comprehensive deflection.

   The on-site test needs to be accurately aligned, while the on-board equipment may not be accurately aligned.
Table 2. The statistics of deflection values at the center point

| Area | Falling ball | Drop weight | Deviation | Area | Falling ball | Drop weight | Deviation |
|------|--------------|-------------|-----------|------|--------------|-------------|-----------|
| 1    | 171          | 177.055     | 6.06      | 21   | 124.98       | 129.46      | 4.48      |
| 2    | 143.01       | 141.33      | 1.68      | 22   | 58.71        | 83.945      | 25.24     |
| 3    | 167.95       | 169.415     | 1.47      | 23   | 79.33        | 110.125     | 30.80     |
| 4    | 116.5        | 134.775     | 18.28     | 24   | 172.85       | 158.27      | 14.58     |
| 5    | 135.41       | 160.595     | 25.19     | 25   | 157.8        | 163.885     | 6.08      |
| 6    | 154.89       | 152.805     | 2.08      | 26   | 161.93       | 153.47      | 8.46      |
| 7    | 116.5        | 146.535     | 30.04     | 27   | 126          | 140.31      | 14.31     |
| 8    | 142.46       | 162.425     | 19.97     | 28   | 189.39       | 186.27      | 3.12      |
| 9    | 97.06        | 132.525     | 35.47     | 29   | 223.76       | 199.51      | 24.25     |
| 10   | 108.37       | 119.42      | 11.05     | 30   | 225.21       | 202.375     | 22.84     |
| 11   | 121.94       | 149.345     | 27.41     | 31   | 161.34       | 163.74      | 2.40      |
| 12   | 189.39       | 181.635     | 7.76      | 32   | 179.74       | 161.31      | 18.43     |
| 13   | 186.78       | 187.5       | 0.72      | 33   | 126.51       | 145.18      | 18.67     |
| 14   | 190.04       | 192.985     | 2.95      | 34   | 153.73       | 155.625     | 1.90      |
| 15   | 98.38        | 117.075     | 18.70     | 35   | 146.35       | 147.24      | 0.89      |
| 16   | 124.47       | 123.655     | 0.81      | 36   | 129.61       | 142.165     | 12.56     |
| 17   | 84.87        | 114.375     | 29.51     | 37   | 159.57       | 156.36      | 3.21      |
| 18   | 60.34        | 77.895      | 17.56     | 38   | 105.13       | 137.335     | 32.21     |
| 19   | 105.13       | 120.545     | 15.42     | 39   | 94.46        | 125.33      | 30.87     |
| 20   | 91.47        | 128.84      | 37.37     | 40   | 114.07       | 132.715     | 18.65     |

Mean of deviation (0.01mm) 15.47
Mean of deviation (0.01mm) 14.70

2) Regional average data fitting

The average value of the falling-ball data from different areas is used to fit the deflection value of the drop weight, and then 5 points of the falling-ball in the same area are fitted to the deflection value of the drop weight. Figure 4 shows the representative average fitting and center point data fitting. The fitting data excludes some abnormalities and field-test-failure area.

It can be seen from the results of the falling-ball test that although the positions of the points in the same area are similar, the differences of test results are large. The test data from the drop weight also have difference, which proves that the uniformity of the subgrade is not good and therefore the data are discrete. As a result, the correlation of the average fitting results is not good enough.

Figure 4. Average fitting.
3) Data fitting of the center point

Figure 5 shows the fitting data of the center points of the test areas. Because the two devices at the center point are generally tested at the same location, the correlation is best for each point. The two devices mentioned above have differences in test area, test depth, test method, and so on, while the commonality is that the test parameters are the same. This test is for non-uniform materials and has a high correlation coefficient. Thus the two devices have the good correlation. In addition, the test depth of falling-ball test is slightly less than the design layer thickness, and the modulus of each layer can be detected individually.

![Data fitting of the center point](image)

**Figure 5.** Data fitting of the center point

3.4. Comparison of test results

The value of falling-ball at the center point and the average value of the surrounding points have a good correlation with the FWD deflection, and the correlation coefficient is 0.87–0.95.

The correlation between the value of falling-ball at the center point and the FWD deflection is better than the average value of the surrounding points, indicating that the material is more discrete.

The intercept of the regression line of the falling-ball value (x) and FWD deflection (y) is greater than 0 and the slope is smaller than 1, indicating that for soft soil (large deflection), the deflection value of the falling-ball test is greater than the FWD test value. For hard soil, the deflection value of the falling-ball test is relatively smaller. In other words, the change rate of the FWD test value is less than the falling-ball, which is because that the two test depth ranges are different. The test depth of FWD is greater than the falling-ball, and the test range is wider, so the rate of change is smaller.

![Comparison of test results](image)

**Figure 6.** Comparison of test results.
4. Conclusion
In recent years, China's highway construction has developed rapidly, and the traditional subgrade deflection detection and evaluation methods have obviously not been adapted to the actual needs of high-grade highway construction and management. In order to reasonably evaluate the construction quality, more comparative test research is needed in order to use more reasonable testing equipment and methods in actual use.

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