Quantity traceability of falling weight deflectometer

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Abstract: Falling weight deflectometer (FWD) is widely used in traffic transport industry. In order to solve the traceability of FWD, the definition of deflection was studied, the use and measurement of FWD was thoroughly analysed, and the measurement parameters were determined. Calibration device, standard foundation, and experimental environmental conditions of FWD were set up. The measurement uncertainty of the calibration equipment has been analysed. Through the test of the typical FWD, the performance of the calibration equipment is tested. Through the establishment of the traceability chain of 'Absolute normal low frequency vibration standard device-FWD calibration equipment-FWD', it can meet the calibration/verification requirements of FWD.

1 Introduction

In the highway industry, the deflection value not only reflects the overall strength and stiffness of each structural layer and soil foundation of the road surface, but also has a certain intrinsic connection with the state of use of the road surface. It can be used for pavement structure evaluation and reflects the overall strength and quality of the road surface. Acceptance of an important test indicator. At present, the equipment for measuring deflection are Beckmann beam (BB), steady-state deflection apparatus (Dynaflect), drop hammer deflection meter (FWD), and automatic deflection instrument [1]. Compared with the traditional BB, the FWD has advantages of fast test speed, high efficiency, high load control accuracy, high test result accuracy, and high data processing speed. Wide range of applications [2]. The FWD was created in the early 1970s and was first developed by France and Sweden. Since the 1980s, the USA, Denmark, the UK, and Japan have introduced or copied such deflection devices. Major manufacturers include Dynatest, JILS, Carl Bro, and KUAB. The application research in China began in the mid-late 1980s. At present, Beijing, Shanghai, Guangdong, Shandong, Tianjin, Zhejiang, and other provinces and cities already have about 30 different models of FWD [1]. Major manufacturers include Shanghai, Zhuozhi Litian, Nanjing Hee-Yong, Wang Gu Shen Jian, Beijing Xingtong Lianhua etc. According to statistics in 2010, the domestic drop hammer deflection meter is no <130 units in China and accounts for 1/5 of the world's total [3]. It is also used in engineering acceptance. With the increase of the usage time, the equipment appears interfaces. Poor contact, quasi-inaccuracy of the sensor, structural instability, and other issues cannot guarantee the accuracy and reliability of the measurement data.

The calibration of FWD was carried out very early. In 1994, the USA established the first FWD calibration specification. In 2007, the US Federal Highway Commission FHWA made improvements to it and added new calibration methods. The USA has four legal national calibration centres located in Pennsylvania, Texas, Colorado, and Minnesota. Denmark, Australia, and South Africa also have FWD calibration centres provided by the USA [4]. The FWD calibration method is generally divided into a reference calibration method and a relative calibration method [5]. According to the JJG (traffic) 133–2017 FWD, the method of tracing the source value of FWD proposed here.

2 Falling weight deflectometer

The flexible pavement will produce vertical deformation under the action of load, and the deformation will recover after the loading. The part of deformation that can be recovered is deflection, which is an important index to reflect the stiffness of pavement directly. The dynamic deflection and the deflection under dynamic load are that the subgrade or pavement under the impact load of a certain weight hammer down to a certain height, usually in the unit of 0.01 mm. The deflection value is one of the qualified standards of road quality in the index of JTG D50-2017 about the highway asphalt pavement design specification.

The equipment for measuring deflection is FWD, which is usually composed of the loading device (including drop hammer, buffer block, bearing plate, and force sensor), the deflection detection device (including deflection sensor, line and signal processing element), and the operating system. The diagram 1 is about the main composition and structure [6]. The FWD uses the seismic wave sensor to measure the deflection, and load sensor to measure the impact load generally [7]. The material will undergo deformation and failure under the strong and continuous loading for a short period of time. The corresponding structure and the properties will undergo permanent changes [8]. Fig. 1 is about the signal variation of typical deflection under the impact of the impact load. The deflection basin data are obtained by collecting the instantaneous deflection of the deflection sensors generally, as the load value on the peak [9].

3 Calibrating device

3.1 Calibrating device

The calibration device is the highest measurement standard in the traffic industry for FWD. The measurement parameter is the deflection (deformation). The calibration equipment is composed...
of weighing sensor, displacement sensor (accelerometer), data acquisition module, control system, upper computer, connection line and standard foundation etc., as shown in Fig. 2.

The FWD is a pulse dynamic deflectometer, which simulates the instantaneous impact of vehicle loads on the road surface and obtains the instantaneous deformation of the road surface. The short impact time, the complex frequency composition, and the non-reproducible process, cause the difficulty of the calibration of the deflection sensor during the impact process of the heavy hammer. Therefore, we must select the sensor with high accuracy and good dynamic performance as the standard of deflection calibration. The impact process of drop hammer can be linearly superimposed by sinusoidal signals of different frequencies according to the theory of impact and linear system. The calibration device adopts the HBM load sensor with the accuracy grade of 0.5% and the accelerometer with a linearity of ±0.03% as the standard device. The fitting curve of the load sensor and deflection sensor of the FWD is calculated to determine the accuracy of FWD’s measurement results according to the verification method prescribed by the JTG (traffic) 133-2017 FWD. Under the impact load is applied by the FWD.

3.2 Standard foundation

As the working process of FWD is an impact process, the speed of impact changes greatly within a very short time, and it is reduced to zero. The structure is affected by the impact. Therefore, the structural design of the standard foundation is very important and stability should be guaranteed. The error sources of the drop hammer deflection instrument include posture error, random error, and offset error [10]. See Fig. 3. If the measured deflection is close to true, random errors will mask the system error. For example, if one measured deflection is 50 μm and the systematic error is 2.0%, the systematic error may be only 1 μm. The random error is 2 μm, and systematic errors can hardly be detected when using statistical methods for measurement. Therefore, the deflection should be large enough to detect systematic errors. According to the JTG (traffic) 133-2017 FWD, referring to the requirements of R32 on the standard foundation, the design foundation is four-layer reinforced concrete, with an area of 1 m × 2 m, a depth of 1 m, and 5 mm foam around. The board serves as a separator. It has been verified by experiments that when the load value is between (70–100) kN, the deflection can reach >300 μm under normal circumstances, and the expected requirements are achieved with good stability.

Fig. 2 Photo of the FWD deflection signal

![Fig. 2 Photo of the FWD deflection signal](image)

Fig. 3 Source of error for FWD

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Fig. 4 Traceability diagram of falling weight deflection

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4 Implementation of traceability chain

The calibration device uses a load cell and a standard accelerometer as the main calibrator. The main calibrator traces the source value through the inspection of the metrology institute. The linearity of the accelerometer obtained by the calibration certificate is ±0.03%. The accelerometer was traced back to the China National Institute of Metrology’s absolute low-frequency vibration standard device, thus forming a ‘Absolute method of low-frequency vibration standard device – Falling Weight Deflection calibration device - Falling Weight Deflection’ traceability chain, traceability chain shown in Fig. 4.

5 Uncertainty assessment

5.1 Mathematical model

The mathematical model for deflection measurements is

\[ L = L_{\text{fwd}} \]

In the formula: \( L \) – The deflection measured by the calibration device, μm; \( L_{\text{fwd}} \) – Deflection measured by a drop hammer deflection meter, μm.

5.2 Sources of uncertainty

Sources of uncertainty for the calibration device include the uncertainty introduced by the higher level measurement standard, the uncertainty (non-linearity, resolution) introduced by the main etalon, and the environment.

5.2.1 Uncertainty introduced by standard devices: The device is calibrated using the absolute method low-frequency vibration standard device with an uncertainty of 0.5% (\( k_1 = 2 \)), and the uncertainty \( u_{k_1} = 0.25\% \) introduced by the standard device.

5.2.2 Non-linearity introduced by the accelerometer: The non-linearity of the accelerometer will affect the measurement results. The accelerometer is calibrated by the upper-level measurement department under the reference condition, and the linearity \( \delta \) is not >±0.03%, and it is considered as a uniform distribution according to the class B rating. The uncertainty introduced by the non-linearity of the accelerometer

\[ u_\delta = \frac{\delta}{k_2} = \frac{0.03\%}{\sqrt{3}} = 0.017\% \]

In the formula: \( u_\delta \) – The uncertainty introduced by accelerometer non-linearity; \( \delta \) – The linearity of the accelerometer; \( k_2 \) – The magnifying factor.
Δ, in accordance with the uniform distribution, half-width $a_3 = 0.01$ μm, $k_1 = \sqrt{3}$. The uncertainty $u_3$ introduced by the resolution of the accelerometer.

$$u_3 = \frac{a_3}{k_1 \times L} = \frac{0.01}{\sqrt{3}L}$$  \hspace{1cm} (3)

In the formula: $u_3$ – The uncertainty introduced by accelerometer resolution; $a_3$ – The half-width; $k_1$ – The magnifying factor; $L$ – The deflection measured by the calibration device, μm.

The procedure requires that the calibration use the (20–40)% drop height of the four calibration intervals, and >60% of the height, the deflection value is generally between (80–350) μm, the maximum value, calculated according to 50 μm, then $u_3 = 0.01\%$.

### 5.2.4 Uncertainty introduced by temperature: The FWD calibration ambient conditions are temperature (10–40)°C. Adjust the laboratory temperature to 10°C and 40°C; the measurement results were shown in Tables 3–5, the absolute value of the difference between the deflection $\Delta = |L_{0a^4} - L_{0a^4}|$, in accordance with the uniform distribution, half-width $a_4 = \Delta$, $k_4 = \sqrt{3}$ and the temperature due to the uncertainty component:

$$u_4 = \frac{\Delta}{\sqrt{3}}$$  \hspace{1cm} (4)

In the formula: $u_4$ – The uncertainty introduced by temperature; $\Delta$ – The half-width; $k_4$ – The magnifying factor.

$L$ – The deflection measured by the calibration device, μm.

According to the formula above, when the hammer height is (20–40)% $u_4 = 25\%$; and the hammer height is higher than 60%, $u_4 = 0.17\%$, the maximum value is calculated.

### 5.2.5 Synthetic uncertainty $u_r$: The influencing factors are independent of each other, and the combined uncertainty is calculated according to the calculation $u_r = \sqrt{\sum u^2}$. The maximum uncertainty of each section is taken as $u_3 = 0.35\%$.

### 5.2.6 Extended uncertainty $U$: Taking $k = 2$, the expanded uncertainty of the calibration device is $U = ku_r$. For safe amplification, the expanded uncertainty of the calibration device is: $U_r = 1.0\%$, $k = 2$.

### 6 Experiment and analysis

Experimental environment conditions:

i. Environment temperature: (0–40)°C;

ii. Relative humidity: < 80%RH test site;
iii. The site is clean, flat, hard, no vacancy and without breakage. There is no vibration source and corrosive gas around it.

The test object include Carl Bro manufacturer FWD-A (including nine sensors), Carl Bro manufacturers FWD-B equipment (including seven sensors), Nanjing Xi Ying company (including eight sensors) and Shanghai Zhuo Zhi Li Tian company FWD (including four sensors). The accuracy test of deflection is based on the verification regulation of JJG (traffic) 112-2015 FWD. It is divided into positive sequence and reverse order, which is divided into positive sequence and reverse order. Ten repeated tests are carried out at each height. The data of 40 FWD measurement data and calibration device are linear fitting, and the correction coefficient $k_1$ and $k_2$ value are calculated, if not >0.005, the average calculation is calculated. The value is used as the correction factor of the sensor.

Carl Bro FWD- A has only two sensors to meet the requirements of deflection accuracy, but the repeatability of deflection meets the requirements of the procedure. Carl Bro FWD-B has 5 sensors, the deflection accuracy meets the requirements, but the deflection repeatability does not meet the requirements; Nanjing Xi Ying company FWD has eight sensors. As of the different batch products, the accuracy of the four sensors is not satisfied, but the repeatability is not in accordance with the requirements; Shanghai Zhuo Li Tian FWD is full of accuracy. The requirement of the foot is not satisfied. The test results show that the standard foundation has good stability. The calibration device can effectively evaluate the metering performance of the FWD equipment and has the ability to carry out FWD calibration.

### Table 5: Deflection repeatability

| Sensor serial number | Carl Bro FWD-A | Carl Bro FWD-B | Nanjing Xi Ying comp | Shanghai Zhuo Li Tian company |
|----------------------|----------------|----------------|---------------------|-------------------------------|
|                      | Order Reverse order | Order Reverse order | Order Reverse order | Order Reverse order |
| 1                    | 0.61 1.21 / / | 3.61 3.05 | 4.83 4.52 | |
| 2                    | 1.04 0.74 6.16 5.98 | / / | / | 4.91 4.58 |
| 3                    | 1.01 0.87 6.85 6.56 | 3.56 2.88 | / | |
| 4                    | 1.08 0.99 6.13 6.03 | 3.83 3.26 | 3.74 3.54 | |
| 5                    | 1.11 1.01 6.31 6.25 | 3.66 3.37 | 4.25 4.08 | |
| 6                    | 1.07 1.04 / / | 3.29 3.09 | / | |
| 7                    | 1.03 1.18 6.30 6.08 | 3.16 3.09 | / | |
| 8                    | 0.97 0.97 6.54 6.23 | 2.99 2.88 | / | |
| 9                    | 1.08 1.19 6.06 5.98 | 3.18 3.00 | / | |

The traceability path ‘Absolute normal low frequency vibration standard device -FWD calibration equipment-FWD’ can fit the metrology of the FWD in the transportation industry and can solve the problem of tracing the source of the value of this kind of equipment.

iii. It is verified by experiments that the calibration device can calibrate the equipment of different manufacturers.

### 7 Conclusion

i. The calibration device set up by the national professional metering station can realise the calibration of the FWD.

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