The Current State and Development Tendency of the FWD Metrology Technology

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Abstract. As the “Outline for Building a Leading Transportation Nation” puts forward, the overall requirement of high quality development, the measurement work of transportation industry plays a much more important role. This paper introduces the measurement technology state of the FWD of the highway pavement bearing capacity measuring equipment, the technical state and error analysis of the equipment are introduced, and the calibration and comparison methods are sorted out, which provide a reference for the next generation of the equipment.

Keywords: Metrology, FWD, technical state, calibration method.

1. Introduction

As the “Outline for Building a Leading Transportation Nation” puts forward the overall requirement of high quality development, the measurement work of transportation industry plays a much more important role. In 2017, the FWD has been included in the evaluation standard of the road traffic industry. At present, there are about 2000 sets/set in the industry. According to the overall construction layout of the country's "One Belt One Road", the development of the road transportation industry is also improving year by year, and most road testing laboratories are in need of increasing qualification projects and improving the level of testing business. Facing the general requirements of the industry development, a large number of testing laboratories need to adopt the road detecting equipment such as FWD. And the domestic manufacturers of the equipment research and development are gradually improving their product levels, Therefore, The FWD is showing a substantial growth trend in china.

This paper introduces the measurement technology state of the FWD of the highway pavement bearing capacity measuring equipment, the technical state and error analysis of the equipment are introduced, and the calibration and comparison methods are sorted out, which provide a reference for the next generation of the equipment.

2. The technical state

2.1. The production situation

The pavement deflection measured by FWD is used to evaluate the pavement structure and calculate the residual life, bearing capacity and required thickness of the structural layer, and the results can be used for project-level or network-level pavement system management. The JGG (Traffic) 133-2017
"Falling Weight Deflectometer " defines that the FWD is the device which detects the bearing capacity of subgrade pavement structure, under the impact load of the action with a certain mass of a heavy falling weight falling a certain height, it can determine the instantaneous deformation of the subgrade or the pavement, which is the dynamic deflection and deflection basin under the action of dynamic load. The FWD is composed of a load generating device (including a falling weight, a buffer block, a bearing plate, and a force sensor), a deflection detection device (including a deflection sensor, a circuit and a signal processing element), and a computing control system. And the main composition and structure is as shown in Fig. 1.

The FWD has the advantages of fast detecting speed, high efficiency, high accuracy of load control, extremely high accuracy of test results, and fast data processing speed [1]. According to the statistics in 2010, the number of FWD is no less than 130 units in china, accounting for 1/5 of the world's total [2], and the main manufacturers are Dynatest, JILS, Carl Bro, KUAB, Which are mainly foreign brands, and the functions and working principles of the various instruments are basically the same. The domestic manufacturers such as Shanghai TIP TOP China, Nanjing XIYING TECH, Beijing JinGuShenJian, Beijing SATCOM ITS etc., which the equipments are basically made based on the principle of imported equipment [3-6].

2.2. The technical state
During the measuring process, the computer control system is used to control the hydraulic system to lift or release the heavy falling weight, therefore, the heavy falling weight will acts on the spring or rubber pad, and then the impact load generated by the heavy falling weight is transferred to the pavement through the bearing plate which is in contact with the pavement. Under the control of the computer, the heavy falling weight can impose a half-sine pulse load on the road surface, causing instantaneous deformation of the pavement, the deformation is detected by the sensors of the FWD at different positions, then the dynamic deflection and deflection basin generated under the dynamic load can be obtained[7].

The Schematic diagram of the working principle of the FWD is as shown in Fig. 1. The FWD is used as a detection equipment of dynamic deflection in highway engineering, and the half-sin load impact of the falling weight is similar to the traffic load of highway, so it can simulate the traffic load of highway well and adjust the loading level. Since all the detection data are collected by computer, the speed of data collection and processing is fast, and the accuracy of the test can be guaranteed at the same time. It is especially suitable for large-scale deflection detection of highway engineering. In addition, the FWD can also evaluate the deflection of the pavement composed of multi-layer pavement structures.
At present, the sensor of the FWD is generally adopted the durable, high-precision, light-weight vibration velocity sensor or velocity sensor, and sealed in a plastic sleeve with internal electronic shield. The installation method of the sensor is divided into screw connection or magnet connection, when the sensor needs to be quickly and easily installed with the sensor base, it is connected by magnet. If the two need to be fixedly connected, they are often fixed by screw threads.

In general, the effective displacement of the sensor is ±2mm and the accuracy is 2.0%. For example, a company's sensor has a natural frequency of approximately 5Hz and the effective moving distance of the vibration block is ±2mm. The fastening magnet is downward and the mounting surface is horizontal, so the sensor can only be used for vertical movement measurements. If the sensor is tilted, the range of measurement will be reduced, but its sensitivity will not be affected. For example, the sensor technical specifications adopt by a manufacturer: natural frequency: 4.7Hz, output impedance: 375ohms, damping coefficient: approximately 0.7(when connected to the system processor), effective displacement of vibration block: 4mm (peak value, such as off-balance +/-2mm) weight: 250g(excluding cables). The detection process of the FWD is the impact vibration. There is a cushioning airbag under or above the mass, the bottom of the load plate is generally cushioned by rubber pad. The shape of the rubber pad is a whole circular plate or four, and The diameter is generally 300mm, and the middle is generally connected by a spring to reduce the impact of the impact process on the test results.

3. The Source of error

The elastic layer theory, finite element theory and discrete element theory, etc. are used in the error source analysis of the FWD, and the elastic model is input in all the analysis methods. The pavement modulus can be calculated by means of the deflection and inverse calculation. However, the deflection accuracy is the main factor affecting the accuracy of the subsequent analysis of the inverse modulus. The data of FWD has the following error sources [8-12]: attitude error, random error, offset error or systematic error. The repeated measurement chart of deflection is sinusoidal frequency distribution, as shown in Fig. 2.

![Fig. 2 Random Error and Systematic Error of the FWD](image)

3.1. The attitude error

When the FWD works at a new test site for the first time, the attitude error comes from the mechanical layout of the sensor (detector or seismograph) on the ground. Because of the roughness and looseness of the road surface, sensors are not always securely placed. And The deflection sensor is placed smoothly through several trial drops without data recording. In order to achieve a good sitting posture, the falling weight should generally not exceed 2-3 times. However, repeated drop falling weight tests also may result in attitude error because of the widely cracked roads.
3.2. The random error

The random error is mainly generated in the analog (voltage) signal digitization process. The conversion from analog to digital is to realize that it can be read and processed by a computer. The FWD calibration system provided by the FWD manufacturer is made the digital signal and the engineering unit display displacement (mm, micron, etc.) consistent. But digital conversion has a slight error, usually one or two least significant bits. The equipment manufacturer claims that the random error is about 1-2 μm per reading, independent of the peak value. And each deflection measurement result contains the random error. Random errors can be positive or negative, but it is impossible to know exactly the value of the random error. However, at the same test point and under the same load, the random error can be reduced (but it cannot be completely eliminated) by taking the average value of several bending peak values as the measurement results.

In order to avoid hitting too many falling weights at the same point to change the performance of the pavement, the level of each load is usually no more than 3-5 falling weights. If the random error is X, the random error of the average value of n falling weights is \( \frac{X}{\sqrt{n}} \). This means that the random error of the average is equal to the random error divided by the square root of the number of observations. For example, taking the average of four falling weights as the result can reduce the random error by half (\( \sqrt{4} = 2 \)).

3.3. The system error

The system error will be generated due to the limitation of sensor calibration. The system error is proportional to the reading. If the deflection doubles, the system error will be about twice the magnitude. There are many sources of systematic error, but FWD manufacturers generally claim that the system error does not exceed 2% of the reading. Therefore, the systematic error can be zero, greater than or less than zero. But unlike random error, systematic error is constant (percentage of reading) for each measurement result of a given sensor.

4. Metrology and calibration technology

4.1. Relative calibration method

The development of the FHWA-FWD calibration specification in the United States mainly refers to the standards established by the auspices of the Federal Highway Commission. In 1994, the United States established the first FWD calibration specification. In 2007, the FHWA improved it and added new calibration methods. The United States has four statutory national calibration centers, which is located in Pennsylvania, Texas, Colorado, and Minnesota. Denmark, Australia and South Africa also have FWD calibration centers provided by the United States. The verification regulation of falling weight deflectometer in china is the JJG (Traffic) 133-2017 "Falling Weight Deflectometer". At present, deflection is measured by displacement sensor, and calibration mainly includes reference calibration and relative calibration.

At present, the calibration device used in our country is developed by the Danish Sweko company, including weighing sensor, displacement sensor (accelerometer), data acquisition module, control system, upper computer, connecting line and standard foundation Etc., the schematic diagram is shown in Fig.1, and the physical diagram is shown in Fig. 3.
FWD is a pulse dynamic deflectometer, which simulates the instantaneous impact of vehicle load on the pavement to obtain the instantaneous deformation of the pavement. During the impact process of the heavy falling weight, the impact time of FWD is short, the frequency component is complex, and the impact process of the heavy falling weight is not reproducible, which makes the calibration of the deflection sensor difficult. Therefore, the sensor with high measurement accuracy and good dynamic performance is selected as the calibration standard for deflection.

Calibration device adopts a standard with the accuracy level of HBM load sensor is 0.5%, and the linearity of plus or minus of the accelerometer is 0.03%. Then the FWD is used to impose an impact load, according to the verification regulation of the JJG (Traffic) 133-2017 "Falling Weight Deflectometer", the fitting curve correction coefficient of FWD load sensor and deflection sensor is calculated to judge the accuracy of FWD results. In order to fully verify theadaptability of the imported calibration equipment, the typical FWD equipment was selected and carried out several tests according to the current verification regulations. However, there are still many problems in the experiment, which are summarized as follows:

4.1.1. Poor applicability. At present, the calibration device developed by Sweco can only calibrate equipment from foreign manufacturers, and the applicability on domestic equipment cannot be verified. In recent years, the research and development level of domestic FWD detecting equipment has been continuously improved, and the imported calibration devices are difficult to meet the needs of verification/calibration because a large number of detecting units have selected domestic manufacturers’ equipment. In addition, due to the poor applicability of the mounting racks to different types of sensors, there are problems of inconvenient installation and difficulty in stable fixation. And it is difficult to choose a rack because the sensor wires of different manufacturers are different in length.

4.1.2. Insufficient functions. The Calibration device processing software needs to run in XP system, there are the following problems: ①The compatibility with other software is poor. ②The amount of data stored in the software is very small, generally no more than 30 experimental samples. Facing the calibration requirement of 2000 sets/set, it is really difficult to meet the requirements. ③The calibration device can only import data from the equipment of the four manufacturers mentioned above, and cannot cover my country's FWD, and cannot realize directly the implement data analysis and issuance of calibration reports in the computer system with the low efficiency.

4.1.3. Various malfunction. During the calibration process, the software often crashes, restarts, jams, missed data, etc., which make the test inefficiency and fail. In addition, the calibration device is an imported device, therefore, the after-sales service capability is weak, and the troubleshooting is time-consuming, the remote maintenance effect is poor, and the introduction of foreign engineers is costly.
4.1.4. Low efficiency. In terms of work efficiency, the general calibration frequency is 1.5h/unit-4h/unit. In addition, it is estimated that it will take about 2-3 hours to disassemble the sensor in the case of skilled technicians. Therefore, the calibration time for a FWD is about half a day, in addition, it takes about 1 hour to issue the certificate and 2 calibration personnel, which is inefficient. Therefore the current calibration efficiency cannot meet the larger needs of the industry.

In summary, in the face of the upgrading and improvement of domestic and foreign drop falling weight deflection instruments, and the calibration requirements of about 200 sets/sets of equipment in my country, as a calibration device developed around 2000, the calibration technology is difficult to meet my country's current verification/calibration needs.

4.2. Absolute calibration method

The calibration device is composed of a case, a motor, a main board, etc. During operation, a calibrated FWD velocity sensor is installed on the rotor of the motor through an installation slot. By controlling the movement of the motor and the vibration frequency range of \((0.4-450)\) Hz, the cutoff frequency, intercept, and maximum offset at amplitude of the velocity sensor is tested to verify the effectiveness of velocity sensor of the FWD. For example, a company that uses a standard vibration table to calibrate the deflection sensor is as shown in Fig.4.

![Deflection Sensor Calibration on the Vibrating Table](image)

Fig. 4 Deflection Sensor Calibration on the Vibrating Table

The relative gain of the deflection sensor is adjusted with the change of the mechanical performance of the deflection sensor lead to the correct output. The purpose of calibration is to determine the calibration factor. The calibration factor is a simple number that is the relative gain multiplied by the new relative gain obtained by the deflection sensor. And in order to find this calibration factor, it is necessary to use Fwd Win to compare the signal measured by the deflection sensor with the signal measured by a calibration box with a high-precision reference accelerometer. The deflection sensor and the reference accelerometer are tightly connected and placed on the same vibration generator, which is controlled by a calibration box to make the deflection sensor's mechanical input consistent with the reference accelerometer. In addition, in order to ensure repeatability and minimize the impact of noise on the calibration coefficient, the calibration coefficient will be will be calculated from the average value of 12 separate impulse The duration and peak value of 12 half-sine wave pulses are shown in Table 1.
Table 1. Duration and Peak Value of 12 half-sine Wave Pulses

| NO. | Duration [ms] | peak value [µ] |
|-----|--------------|----------------|
| 1   | 7.5          | 125            |
| 2   | 12.5         | 125            |
| 3   | 17.5         | 125            |
| 4   | 22.5         | 125            |
| 5   | 7.5          | 300            |
| 6   | 12.5         | 300            |
| 7   | 17.5         | 300            |
| 8   | 22.5         | 300            |
| 9   | 7.5          | 500            |
| 10  | 12.5         | 500            |
| 11  | 17.5         | 500            |
| 12  | 22.5         | 500            |

Compare the peak signal obtained from the deflection sensor with the peak signal obtained from the reference accelerometer for each pulse, then this ratio is the calibration factor obtained for each pulse. Finally, take the average of the 12 ratios as the final calibration factor.

4.3. Reference calibration method

The reference calibration method is to calibrate with a sensor which the accuracy is more than 3 times higher than the sensor being calibrated. And it is mainly composed of 4 parts: the base of foundation, deflection calibration device, FWD, control host (computer, capture card and corresponding software). The working principle of the reference calibration method is as shown in Fig. 5. First, the bracket equipped with calibrated sensor is fixed on the ground, then the lower end of the screw rod is fixed with the bracket, and the upper end is extended into the cavity of the standard displacement sensor, so that the relative positions of the ground, the bracket and the screw rod are fixed. During calibration, the falling weight impacts the ground, and the standard displacement sensor detects the displacement of the screw rod driven by the deformation of the ground, and this displacement is the deflection which is equal to the ground deformation. Then the deflection is detected by the standard sensor and the calibrated sensor at the same time, and is collected by the control host and read by the FWD software. At the same time, the vibration of the datum line beam is measured by the speed sensor to eliminate the influence of the beam vibration on the calibration accuracy. Finally, the calibration factor of the deflection sensor can be obtained by comparing the readings of the standard sensor with the calibrated sensor.

Fig. 5 Longitudinal Profile Section of Reference Calibration Device
In order to ensure the accuracy of the calibration, the following measures have been taken in actual operation: ① In order to make sure the base and the foundation of the base are stable, and the datum line beam is not affected by the ground settlement, the foundation of the base where the datum line beam is placed must be constructed separately. To meet the strength of the test ground and sensor range, the yellow sand layer should be isolated from the test ground, as shown in Fig. 5. ② In order to ensure the power supply for equipment and lighting, 220V AC power supply is configured, and the average illumination is > 500lx. ③ The ambient temperature is maintained at 20±10℃, and an exhaust device is installed. ④ Make sure the level of the datum line beam and the displacement sensor are regularly maintained, the tightness of the bracket, the position of the screw rod and the cleanliness of the load sensor are all checked.

The Load sensor calibration also adopt high-precision sensors. The load calibration device mainly includes: a load plate equipped with a high-speed standard sensor, a guide block, an industrial computer with calibration software, and FWD. First, install the guide block on the standard load plate equipped with high-precision standard load sensor, and place them on the ground with sufficient strength, then make the standard load plate and calibrated load plate completely rigid contact through the guide block, the FWD falling weight is impacted on the ground. Then the impact load is detected by the standard load sensor and the calibrated load sensor at the same time, and is collected by the control host and read by the FWD software. Finally, the load calibration factor can be obtained by comparing the readings of the standard load sensor with the calibrated load sensor.

4.4. Other verification methods
The Relative calibration is to detect the comparability of readings between different sensors, with the purpose of reducing the relative errors. The relative calibration method is generally performed once every half a year. Relative calibration should be carried out before use, after replacement or repair, left aside for too long, or abnormal test results. The equipment is a special shelf provided by the manufacturer, with 10 seats for installing sensors, as shown in Fig.6. This shelf has sufficient rigidity to ensure that the vertical vibration of each point on the shelf is basically the same under the load, so that the vibration signal of each sensor seat in the vertical direction is close enough to the vibration signal from the bottom of the shelf. The basic principle of relative calibration is that the ratio of the average value of each sensor to the overall average value should be within the range of 0.997 - 1.003. Otherwise, the relative error is deemed to not meet the accuracy requirements and needs to be adjusted. Or replace the sensor.

Fig. 6 The Relative Calibration Method of the FWD

4.5. Comparison method
The comparison method is to analyze a certain number of the FWD and can realize the value traceability. The top surface of the standard load sensor is the same size as the bearing plate of the FWD. During the test, the bearing plate of the deflection meter is placed on the top of the standard
load sensor. When the falling weight impacts the ground, the load valve is detected by the standard load sensor and recorded by the collector. The repeatability test of the standard load sensor adopts a typical FWD, and the test site is shown in Fig. 7.

Fig. 7 Repeatability Test of Standard Load Sensor

5. Development and prospects
At present, the performance evaluation methods of falling weight deflection instrument mainly include relative calibration method, absolute calibration method, reference calibration method, and other measurement methods. The relative calibration method is adopt by the current verification regulations. It can generally evaluate the technical performance of the equipment well. However, there are problems of low efficiency and poor adaptability, which cannot fully meet the needs of industry calibration in actual verification. The absolute calibration method is a necessary supplement to the relative method. It can evaluate the accuracy of the displacement measured by each sensor and give the indication error. The detecting method based on a stable platform can effectively improve the reliability of the test results, which is a technical situation that the comparison method cannot complete. However, there is no calibration capability in our country at present, and the method is not included in the verification procedures, and there is no necessary requirements or the accuracy and reliability of the evaluation results. Therefore, the necessary supplements can effectively improve the service capabilities of the industry. The comparison method can only evaluate the discreteness of the data between the equipment, and cannot give an evaluation result of whether the equipment is true, so the comparison method cannot fully achieve the goal of uniform value in the industry. Other measurement methods, including the method of comparing sensors with each other, can only observe the situation between the sensors of one device, but have a bad impression of the overall situation. Other vibration table methods can only calibrate Dannate brand equipment, and provide a sine wave waveform, which cannot fully simulate the actual shock wave, so the measurement of the shock displacement of the equipment is not convincing. Based on the above discussion, it is necessary to develop a calibration method for the equipment under multiple methods in order to form a systematic method for the value traceability of the FWD and avoid the constraints caused by a single method.

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