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**Research paper**

# Rapid evaluation method of subgrade performance using Portable Falling Weight Deflectometer

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**Abstract:** The performance evaluation of new and old subgrades is critical for the quality and safety of reconstruction and extension projects. It is necessary to achieve rapid and easy performance testing. In this study, a Portable Falling Weight Deflectometer (PFWD) is chosen to rapid evaluate the performance of subgrade. First, a testing area, the reconstruction and expansion project of the Hefei to Dagudian section of the Shanghai-Shaanxi Expressway, is selected. Then, the PFWD modulus $E_p$ of resilient tested by PFWD and the corresponding water content $w$ and compacting degree $K$ tested by the cutting ring method for old subgrade are obtained. And the correlation relationship between $E_p$ and $w$ and $K$ is established. The performance of old subgrade can be rapid obtained by PFWD. Meanwhile, for the new subgrade, the correlation relationship between $E_p$ and bending value $L$, $w$ and $K$ is established, and the performance can also be rapid tested by PFWD. Finally, a rapid evaluation method for the reconstruction and expansion of subgrade performance was proposed, which aims to provide technical support for ensuring construction quality and safety and provides a technical reference and a theoretical basis for the prediction of similar subgrade performance.

**Keywords:** portable falling weight deflectometer, subgrade performance, rapid test, reconstruction and extension project

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# 1. Introduction

With the rapid development of the economy and society, many highways do not meet the requirements for the increasing traffic volume in China, leading to frequent traffic jams and accidents. Thus, they need to be urgently reconstructed or widened to alleviate this situation. However, there are two major challenges facing the expansion and reconstruction of expressways: 1) to minimize the impact on traffic, the construction period of general reconstruction and expansion projects is relatively tight [1, 2]. 2) after years of operation and under the influence of traffic load and natural environment, the performance of the old road subgrade is often substandard [3–8]. Therefore, it is particularly important to promptly make an accurate evaluation of the performance of the new and old road subgrade and to provide technical support for the high-quality and safe construction and operation of the reconstruction and expansion project.

In China's current specifications, the resilience modulus is used as the design index, thereby reflecting the bearing capacity of the subgrade [9]. During the actual field testing process, the detection methods of resilient modulus chiefly comprise the bearing plate method, the Benkelman beam deflection method, and the Falling Weight Deflectometer (FWD) method [10, 11]. The detection result of the bearing plate method represents the static resilient modulus; nevertheless, this method is time-consuming and labor-intensive, and data processing is relatively complex [12]. In contrast, the Beckelman beam method is a commonly utilized detection method in the construction of expressways and is suitable for measuring the resilient and deflection of various subgrades to analyze their overall bearing capacity. In this way, the static resilient deflection under a static automobile load is measured, and the resilient modulus is reversed [13]. However, the subgrade is subjected to dynamic load in the actual working process, and all of them require manual operation during the testing process. Besides, the test results are considerably impacted by human factors, and the test has poor adaptability, slow speed, low accuracy, and poor reliability [14]. Lastly, the FWD method uses an FWD to test the instantaneous deformation of the top surface of subgrade under impact load, that is, dynamic deflection, and then the resilient modulus is calculated according to the measured deflection value to evaluate the bearing capacity of subgrade [15, 16]. Although the index acquired by FWD detection is a dynamic index, its equipment is large, needs to be towed to the site by tractor, and has certain requirements for the detection site. In practice, it is rather complicated for tractors to reach the site. Moreover, the equipment is costly, the sensor is easily contaminated during detection, and the detection data is easily distorted [17, 18]. Therefore, there is an urgent need to develop a fast and convenient approach to evaluate subgrade performance and control construction quality for reconstruction and expansion projects.

Dynamic modulus tests based on PFWD and the penetration rate test based on the dynamic cone penetrometer (DCP) are two novel rapid detection methods developed in the recent decade [19–22]. During detection, the weight hits the loading plate surface after free fall, and the sensor instantly measures the induced deflection. Several studies have been conducted to examine the detection efficiency of PFWD methods in geotechnical engineering. Alessandro Marradi at al. (2014) [23] confirmed the reliability of LWD in the quality control of road engineering through results obtained at two test sites. In another instance, Amir Kavussi at al. (2010) [24] performed PFWD tests in sections of selected road sections in different projects in Tehran and described a significant correlation between the PFWD modulus, FWD, and CBR. Similarly, Varghese George at al. (2009) [25] compared results obtained using PFWD with those acquired using conventional methods (e. g. CBR and DCP) to investigate the correlation between these methods in red clay areas of India. Lin at al. (2006) [26] performed field DCP and laboratory CBR tests, compared the results with PFWD, and described that among the loading plate size, the contact surface flatness, and the drop height, the loading plate size had the greatest influence on the results of PFWD. Varghese George at al. (2018) [27] also conducted a detailed study on the resilient modulus of laterite in southern India, compared the results with those of PFWD, and determined that the resilient modulus measured by the two methods was comparable, while the replacement was feasible with cheaper PFWD. In short, the resilient modulus of the PFWD test and the traditional subgrade performance index can be used for the rapid detection of subgrade performance on site [28], but the performance detection of old and new subgrade in the reconstruction and expansion project is limited, especially for the detection of low liquid limit clay subgrade.

As mentioned above, the load-bearing plate method, Benkelman beam method, and FWD method are time-consuming and complicated to operate. PFWD testing, though, is a non-destructive and rapid testing method. However, the results cannot be used for subgrade evaluation and need to be correlated with the basic properties of subgrade moisture content $w$ and compactness $K$ obtained by traditional methods. The construction time of improvement and expansion projects is often limited. Therefore, reasonable and rapid testing of performance indicators such as water content, compaction, resilient modulus, and deflection of subgrades is essential for the maximum utilization of existing subgrades.

Therefore, this paper relied on the reconstruction and expansion project of the Hefei-Dagudian section of the Shanghai-Shaanxi Expressway to analyze clay subgrade with a low liquid limit. Firstly, $E_p$, compactness, and water content were measured by PFWD and ring sampler tests on the old subgrade, and then the functional relationship between the three was established. Next, the PFWD, Benkelman beam, and ring sampler methods were used to calculate the $E_p$, bending value $L$, moisture content $w$, and compacting degree $K$ of the new subgrade, respectively, and the functional relationship between $E_p$ and each index was subsequently established. Finally, a rapid detection method for new and old subgrade of reconstruction and expansion projects based on PFWD was proposed, which provides technical support for guaranteeing construction quality and safety.

## 2. Research area

This study relied on the renovation and expansion project of the Hefei-Dagudian section of the Shanghai-Shaanxi Expressway. The project starts from the intersection of the G40 Shanghai-Shaanxi Expressway from Hefei to Dagudian and the S17 Banghe Expressway and ends at the Dagudian Junction. As is well known, it has been open to traffic for nearly 15 years. With a total length of 102.66 km, it is a major channel for vehicles from the Yangtze River Delta region to enter Hubei, Sichuan, southern Henan, Shaanxi, and northwest China, as well as the main highway connecting Hefei's economic circle. The entire highway has been expanded from a two-way four-lane to a two-way eight-lane without a widening section. The width of the subgrade following widening is $7 \times 2 + 28 = 42$ m. Notably, the designated speed limit is 120 km/h, and there is no superelevation in the whole main line. This area belongs to the north-south climate transition zone of China, with mild and humid climates, four distinct seasons, moderate rainfall, and sufficient sunshine. Low-liquid limited clay is predominantly distributed along the route and used for filling new and old subgrades. The subgrade of the K659 + 820 ~K659 + 920 section of the project was selected for investigation. With reference to the 'Technical Specification for Highway Soil Test' (JTG3430-2020), two kinds of soil samples of new and old subgrades were classified and their material parameters were determined. The tests included particle sieving test, boundary moisture content test and compaction test. Their basic physical parameters were evaluated, including the soil sample classification curves are shown in Fig. 1. Maximum dry density, optimum moisture content (OMC), liquid limit, plastic limit, plasticity index and other basic physical parameters are shown in Table 1. Combined with the obtained in situ soil particle gradation, the mass percentage of soil particles in the fines group of each soil sample is greater than 50%, the liquid limit of each soil sample is less than 50%, and the plasticity index is greater than 7%, which can indicate that both the old and new subgrade soil samples are low liquid limit clay (CL).

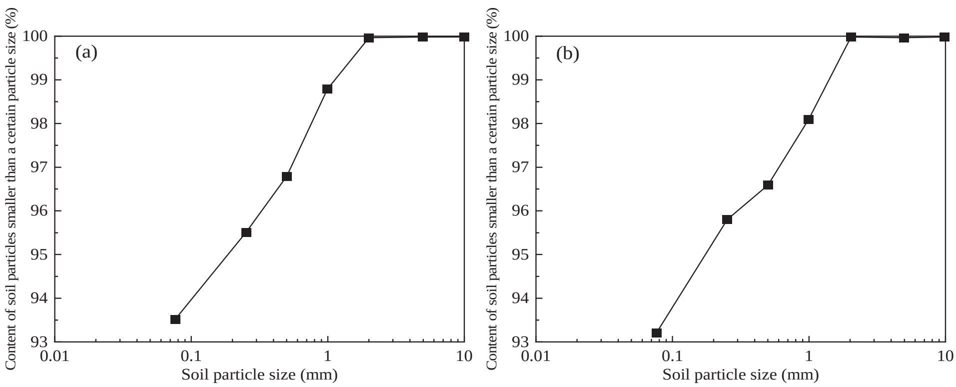



Fig. 1. Subgrade soil sample gradation: a) New subgrade; b) Old subgrade

Table 1. Physical parameters of soil samples

| Soil | Plasticity Index | Liquid limit | Plasticity Index | Optimum Moisture content | Maximum dry density |
|---|---|---|---|---|---|
| New subgrade | 17.8% | 39.2% | 21.4% | 15.1% | 1.84 g/cm$^3$ |
| Old subgrade | 27.7% | 48.9% | 21.2% | 14.7% | 1.77 g/cm$^3$ |

# 3. Establishment of old subgrade performance detection and prediction equation

## 3.1. PFWD test principle

The PFWD model used in this study was PRIMA100, manufactured by Sweco Danmark A/S. The schematic diagram is illustrated in Fig. 2. PFWD consists of a loading system, a data acquisition system, and a data transmission system. The loading system consists of a drop hammer, a sliding rod, a locking rod, and a rubber pad. The data acquisition system is composed of a pressure sensor, displacement sensor, and acquisition device. Lastly, the data transmission system consists of a computer, a wired data transmission device, a wireless data transmission device, and data processing software. Its working principle is to use a certain mass of the drop hammer from a certain height of free fall, a damping device, and a bearing plate to generate instantaneous impact on the subgrade. The drop hammer converts kinetic energy into potential energy by compressing the buffer and produces a half-sine-wave impact load. By collecting the peak bending value at the center of the load, the subgrade resilience modulus can be calculated according to the following formula Eq. (3.1).

$$M_R = \frac{\pi}{4}\frac{2P_{\max}R(1-\mu^2)}{w} \tag{3.1}$$

where: $P_{\max}$ – denotes the peak value of impact load, $R$ – represents the radius of the bearing plate; $\mu$ – is the Poisson ratio; $w$ – represents the springback deformation under load.

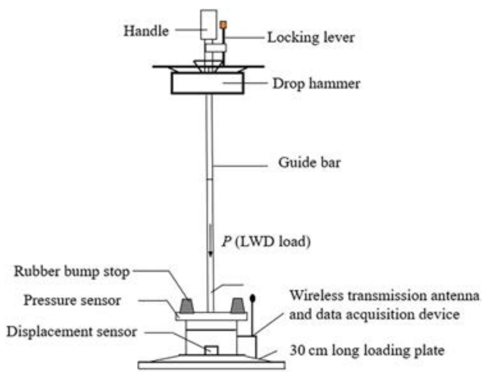



Fig. 2. Equipment schematic of PFWD

## 3.2. Field test scheme

The height of the old subgrade is 4.5 m, and the excavation steps are divided into four steps. The transverse width of the three steps near the bottom is 1 m, and the fourth step is 1.5 m wide, which were marked as S1, S2, S3, and S4, respectively, as displayed in

Fig. 3. Taking K659 + 820 as the starting point, a measuring point was placed in the middle of the transverse position of each step, and the spacing was set to 5 m along the driving direction. A total of 80 measuring points were set, and PFWD modulus, moisture content, and compactness were assessed at each measuring point. The field test is shown in Fig. 4.

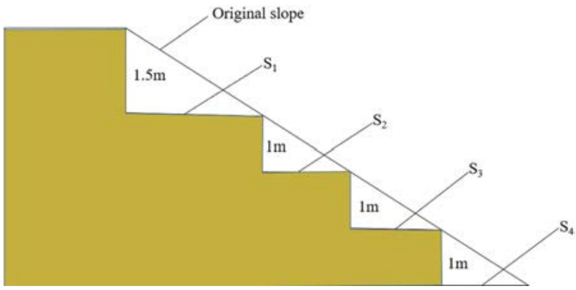
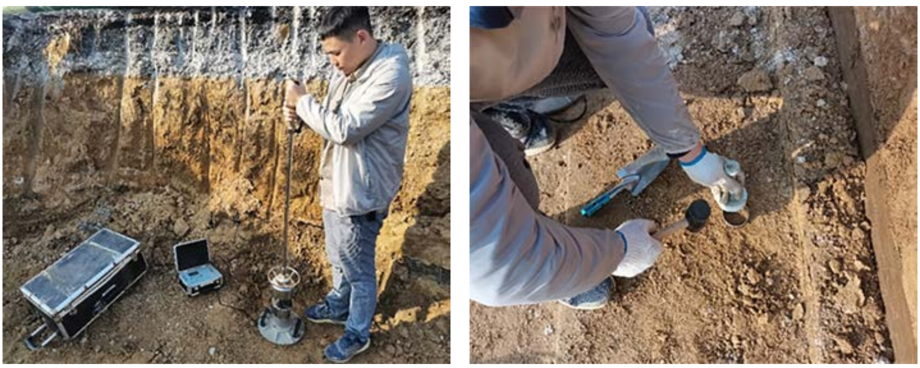



Fig. 3. Old road subgrade step excavation schematic diagram



(a) (b)

Fig. 4. The field test: a) PFWD test of old subgrade; b) In-situ sampling of water content and compactness of old subgrade

## 3.3. Detection data analysis and prediction equation establishment

### 3.3.1. Detection data analysis

The control variates were employed to explore the relationship between resilience modulus, compactness, and water content. More specifically, when one factor was fixed, the influence of another factor on the PFWD test results was analyzed. In the field test, resilient modulus $E_p$ and water content w under two compacting degrees, 0.872 and 0.883, were selected to explore the influence of water content on $E_p$. As shown in Fig. 5. At the same time, the resilient modulus $E_p$ and compactness $K$ were selected under three different water contents, namely 0.164, 0.171, and 0.181. The results are presented in Fig. 6. As can be deduced from Fig. 5, the resilient modulus decreased with an increase in water content because the increase in water content resulted in a decrease of matric suction in unsaturated subgrade soil and a reduction in soil strength. As can be visualized in Fig. 6, the resilient modulus also increased with an increase in compactness because the denser the subgrade soil, the higher the strength performance. Liu et al. (2018) [29] investigated the elastic modulus of six foundation soils and evinced that the dynamic elastic modulus of soil was positively correlated with confining pressure and compaction but negatively correlated with water content, and our test results were consistent with their findings. However, it is worthwhile emphasizing that the fluctuation in dynamic elastic modulus under different influencing factors varies with the type of subgrade soil. In the dynamic modulus of elastic modulus prediction model, the nonlinear parameters of the predictive model are related to loading frequency, stress level, compaction, and water content.

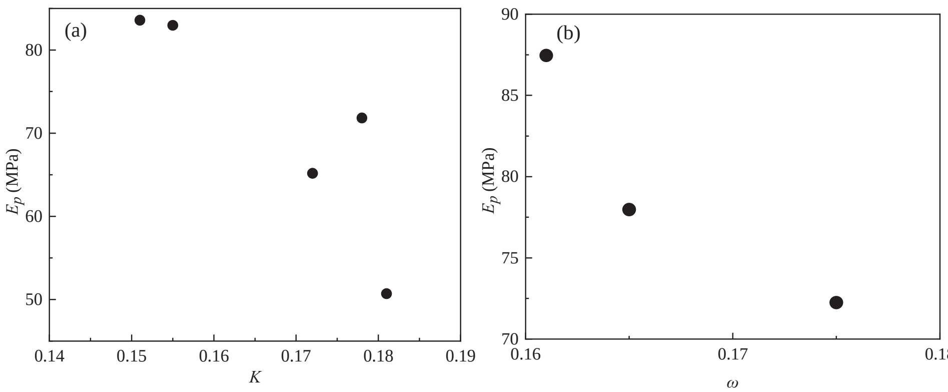



Fig. 5. The relationship between $E_p$ and $w$ of the old road: a) When the compacting degree is 0.872; b) When the compacting degree is 0.883

Furthermore, the springback modulus $E_p$ decreased with an increase in $w$ and increased with an increase in $K$, indicating that an increase in humidity and the loss of compaction of the old subgrade lowers the PFWD modulus of the old subgrade. Considering that the subgrade exhibited strong nonlinear characteristics, stress, and humidity, other factors can significantly affect its mechanical properties. The compaction of the subgrade is a pivotal part of the construction and plays a key role in enhancing the stability and strength of the subgrade. The resilient modulus of the subgrade is primarily affected by the compaction degree of the subgrade under the condition of certain soil quality and moisture content. The greater the degree of compaction, the higher the bearing capacity of the subgrade, the higher the strength, and the greater the resilient modulus. Conversely, the smaller the load-bearing capacity, the lower the strength and the smaller the resilient modulus. Moisture content is another important factor affecting the resilient modulus. When the moisture content is substantially low, the resilient modulus increases with an increase in moisture content. In contrast, when the moisture content exceeds a certain value, the resilient modulus decreases with an increase in moisture content.

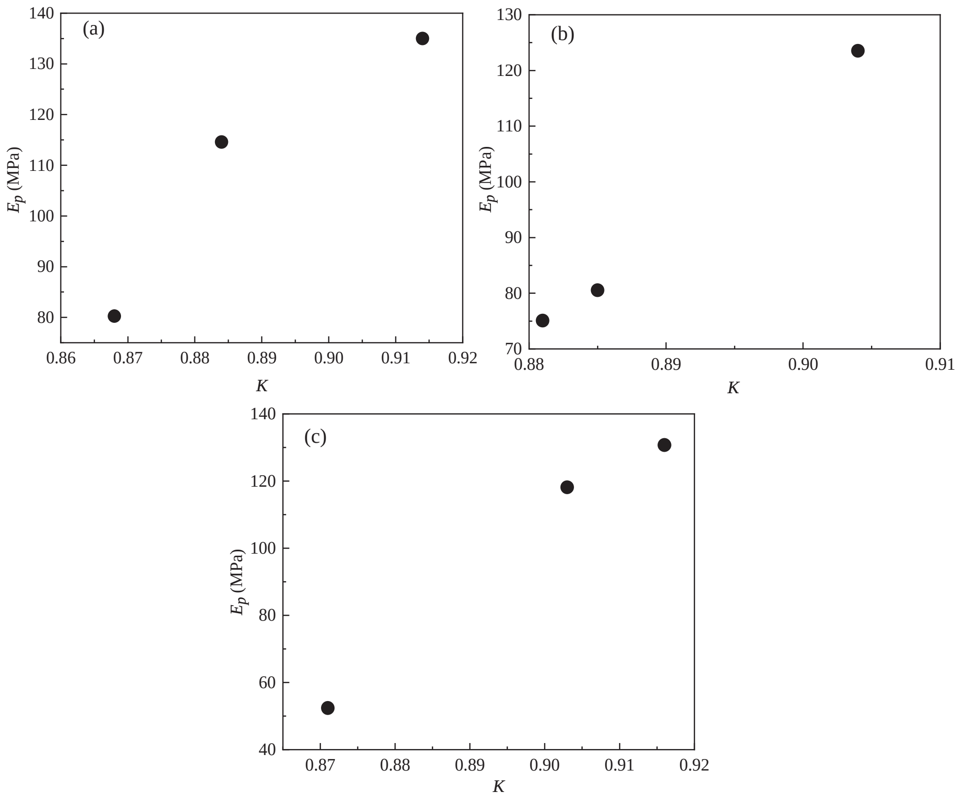



Fig. 6. The relationship between $E_p$ and $K$ of the old road: a) When the moisture content is 0.164; b) When the moisture content is 0.171; c) When the moisture content is 0.18

### 3.3.2. Establishment of the prediction model

According to the above analysis, an increase in subgrade moisture content $w$ and a decrease in compactness $K$ both leads to a decrease in modulus $E_p$, inferring that the modulus $E_p$ is affected by both. The negative effect of water content on the dynamic resilient modulus can be explained by the fact that as the water content in the soil increases, the water film on the surface of soil particles becomes thicker and it is simpler for soil particles to carry out relative displacement, leading to an increase in the resistance deformation of the soil sample. At the same time, when the soil sample with higher water content is loaded, the gas in the pore space is compressed and the pore water pressure increases, which in turn leads to a decrease in the effective stress in the soil body and eventually causes a decrease in the stiffness of the soil sample. The positive effect of compaction on the dynamic resilient modulus can be explained by the fact that as the compaction of the soil sample increases, the alignment between soil particles increases tighter, producing less deformation and more stiffness at the same stress level.

Therefore, $w$ and $K$ were selected as bivariable, and power functions were used to fit the 80 groups of field test results, and the functional relationship between $E_p$, $w$, and $K$ was established as shown in Eq. (3.2), where the standard atmospheric pressure (Pa) was multiplied to ensure dimensional unity. As delineated in Fig. 7, by comparing the measured value with the predicted value, the accuracy of the model was determined to be $R^2 = 0.78$, indicating that the model was reliable. The compactness index of an old subgrade can be quickly obtained by using this model in conjunction with PFWD and water content test, which can be used to evaluate subgrade performance and provide robust technical guidance for design and construction.

$$E_p = 2.93 P_a w^{-0.24} K^{13.99} \tag{3.2}$$

where: $P_a$ – the standard atmospheric pressure, $w$ – represents the springback deformation under load, $K$ – compaction.

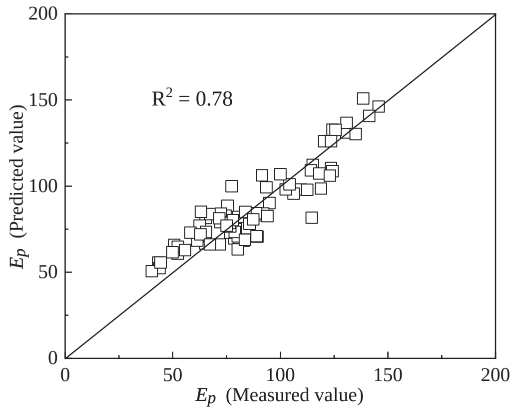



Fig. 7. Comparison of $E_p$ model predicted values and measured values

# 4. Establishment of new subgrade performance detection and prediction equation

## 4.1. Field test scheme

When a new subgrade is accepted, the representative value of the deflection of the subgrade top surface measured on the road section is smaller than the acceptance deflection value of the subgrade top surface. Therefore, the deflection value is a crucial detection index for the new subgrade. Classical deflection detection methods, such as the Benkelman beam, FWD, and bearing plate test, not only necessitate large loads such as vehicle loads but also require more personnel, which is time-consuming and laborious. Regarding remote detection, the equipment must be transported over a long distance, which is also time-consuming and burdensome.

The $E_p$, deflection $L$, compaction degree, and moisture content of the subgrade were tested by PFWD, Benkelman beam, and sand filling methods, as well as a drying experiment. In the process of paving the subgrade in the test section, a total of 60 measuring points were established every 5 meters along the driving direction at the top of District 93, the top of District 94 the top of District 96. The field test situation is shown in Fig. 8.

(a) (b)

Fig. 8. The field test: a) Field Benkelman beam test; b) Field compaction test

## 4.2. Detection results and prediction equations

Through the field test, the indicators for each measurement point of the new subgrade were obtained, as listed in Table 2. A total of 60 groups of test data were collected.

Table 2. Performance of spliced subgrade and test results of PFWD

| Stakemark | The compactness 93% | | | | The compactness 94% | | | | The compactness 96% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) |
| K659+820 | 139.5 | 90 | 94.5 | 14.6 | 138.7 | 90 | 94.8 | 15.2 | 131.4 | 70 | 96.1 | 17.1 |
| K659+825 | 137.9 | 86 | 94.7 | 14.3 | 131.3 | 92 | 94.6 | 15.3 | 156.5 | 66 | 96.4 | 17.2 |
| K659+830 | 86.2 | 98 | 93.4 | 15.8 | 129.8 | 88 | 94.5 | 15.4 | 172.0 | 72 | 96.6 | 16.7 |
| K659+835 | 62.6 | 114 | 93.5 | 16.2 | 170.4 | 84 | 94.9 | 14.6 | 152.8 | 78 | 96.7 | 16.4 |
| K659+840 | 109.2 | 90 | 94.2 | 15.1 | 136.6 | 88 | 94.5 | 15.4 | 144.4 | 66 | 96.3 | 16.7 |
| K659+845 | 64.5 | 118 | 93.2 | 16.5 | 81.4 | 96 | 94.3 | 16.5 | 189.2 | 64 | 96.9 | 16.3 |
| K659+850 | 134.1 | 86 | 94.4 | 15.2 | 87.6 | 94 | 94.1 | 15.7 | 192.1 | 64 | 96.8 | 16.5 |
| K659+855 | 104.8 | 88 | 93.9 | 15.6 | 118.5 | 90 | 94.5 | 15.9 | 200.4 | 66 | 97.5 | 16.2 |
| K659+860 | 74.0 | 96 | 93.5 | 16.1 | 113.6 | 92 | 94.2 | 15.6 | 145.1 | 72 | 96.3 | 17.6 |
| K659+865 | 122.4 | 84 | 94.5 | 14.6 | 165.6 | 88 | 95.1 | 15.9 | 196.5 | 64 | 96.8 | 16.9 |

*Continued on next page*

Table 2 – *Continued from previous page*

| Stakemark | The compactness 93% | | | | The compactness 94% | | | | The compactness 96% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) | $E_p$ (MPa) | $L$ (0.01mm) | $K$ (%) | $w$ (%) |
| K659+870 | 94.5 | 94 | 93.6 | 15.6 | 103.6 | 94 | 94.7 | 15.7 | 196.9 | 66 | 96.2 | 16.8 |
| K659+875 | 104.4 | 96 | 93.9 | 15.4 | 204.8 | 84 | 94.8 | 14.8 | 200.8 | 62 | 97.3 | 16.5 |
| K659+880 | 96.6 | 98 | 93.7 | 15.2 | 150.7 | 82 | 94.5 | 15.3 | 236.9 | 58 | 97.6 | 16.1 |
| K659+885 | 106.4 | 92 | 93.8 | 15.6 | 233.5 | 76 | 95.6 | 14.4 | 235.6 | 56 | 97.9 | 15.8 |
| K659+890 | 133.2 | 90 | 94.6 | 13.8 | 90.5 | 98 | 94.2 | 16.4 | 117.2 | 78 | 96.2 | 17.5 |
| K659+895 | 102.4 | 100 | 94.2 | 14.7 | 201.2 | 78 | 94.9 | 14.6 | 248.2 | 60 | 97.6 | 15.9 |
| K659+900 | 65.1 | 116 | 93.5 | 16.8 | 122.8 | 92 | 94.8 | 15.8 | 249.1 | 50 | 97.8 | 15.7 |
| K659+905 | 88.4 | 104 | 93.3 | 16.3 | 120.6 | 90 | 94.5 | 16.2 | 134.1 | 74 | 96.1 | 17.9 |
| K659+910 | 108.0 | 96 | 93.8 | 15.1 | 127.9 | 84 | 94.7 | 16.1 | 218.1 | 64 | 97.4 | 16.5 |
| K659+915 | 133.2 | 90 | 94.7 | 14.8 | 82.1 | 102 | 94.1 | 16.3 | 205.9 | 62 | 97.2 | 16.3 |

#### 4.2.1. The relationship between resilient modulus $E_p$ and deflection $L$

According to the test data of the 60 measuring points, the correlation between the modulus $E_p$ of the portable drop weight bending instrument (PFWD) and the bending of the spliced subgrade was determined, as depicted in Fig. 9. As can be seen in the figure, $E_p$ was negatively correlated with the bending value $L$, and the resilient modulus $E_p$ showed a linear decreasing trend with an increase in the bending value $L$. Based on this, a linear equation was established to predict their relationship, as shown in Eq. (4.1). To evaluate the predictive accuracy of the equation, the field-measured $E_p$ value was substituted into Eq. (4.1) to predict the bending $L$, which was then compared with the measured bending

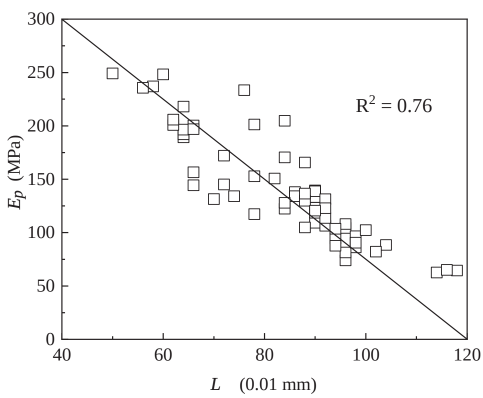



Fig. 9. The law of change of $E_p$ with $L$

value of the Beckmann beam. The results are presented in Fig. 10. The accuracy of the model was $R^2 = 0.78$, implying a robust predictive value. Based on this, PFWD can be used to quickly detect the bending of the new subgrade.

$$E_p = -2.8598L + 380.96 \tag{4.1}$$

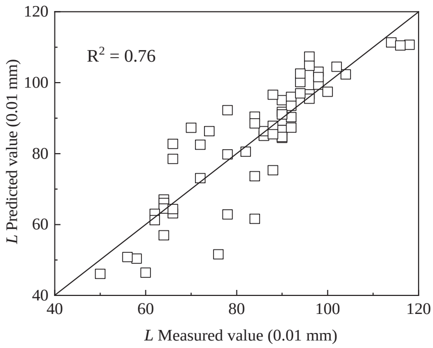



Fig. 10. Comparison between the predicted and measured values of the $L$ of reconstruction subgrade

#### 4.2.2. The relationship between resilience modulus $E_p$, compactness, and water content

Consistent with Section 3, the correlation between the PFWD modulus of the new subgrade established in the form of bivariable power, water content, and compactness of the spliced subgrade is shown in Eq. (4.2). To analyze the regression accuracy of the model shown in Eq. (4.2), the measured compactness and water content$E_p$ were used to estimate the resilience modulus, and the results were compared with the measured values. The results showed that the predictive value was satisfactory, with $R^2 = 0.78$, as illustrated in Fig. 11.

$$E_p = 0.039P_a w^{-2.54} K^{22.83} \tag{4.2}$$

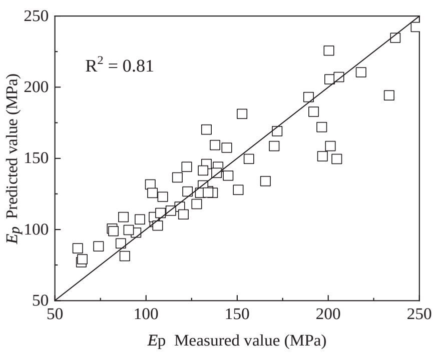



Fig. 11. Comparison of $E_p$ model predicted values and measured values

# 5. Conclusions

Based on the reconstruction and expansion project of the Hefei to Dagudian section of the Shanghai-Shaanxi Expressway, PFWD tests were carried out at several test points in section K659 + 820 ~ K659 + 920 of the first section, and a field test method was proposed for timely estimation of the performance of the reconstruction and expansion subgrade.

1. The correlation between the PFWD test index $E_p$, moisture content, and compacting degree of the new and old subgrade was established using the bivariable power model, and an engineering application method was designed to swiftly predict the performance of new and old subgrade using the PFWD test.
2. The spliced subgrade was tested by a Beckmann beam and portable drop weight bending instrument (PFWD). The PFWD modulus $E_p$ of spliced subgrade was negatively correlated with the bending value $L$ of spliced subgrade, and the correlation between the two was established by a linear equation. An engineering application method was developed to quickly assess the buckling performance of spliced subgrade by the PFWD test.

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