RESEARCH ARTICLE

Using portable falling weight deflectometer to determine treatment depth of subgrades in highway reconstruction of Southern China

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Abstract

Based on a highway reconstruction project in southern China, this study aims to put forward a method to determine the proper treatment depth of the existing subgrade. First, some field tests including the Beckman beam deflection test and portable falling weight deflectometer (PFWD) test were carried out. The results showed that there was a good correlation between the Beckman beam deflection (L) and PFWD modulus (Ep). Subsequently, a subgrade section was excavated and backfilled with cement-stabilized soil in layers. Compaction test, dynamic cone penetrometer rate test, plate load test and Beckman beam deflection test were performed to evaluate the treatment effect. To make sure, the subgrade was treated deeply enough, the Beckman beam deflection (L) was used as the controlled indicator among all the measured indexes for it was the hardest metric to meet. According to the design deflection and decreasing law of the measured deflections with the different number of the stabilized layers, the treatment depth was finally determined. As the PFWD test is superior to the deflection test in the detection efficiency, and the deflection value can be calculated from PFWD modulus by correlation formulas, thus the latter index can be used as a more suitable parameter for estimating the treatment depth instead of the former. Consequently, based on the measured PFWD moduli of the existing subgrade, six treatment schemes considering different treatment depths were proposed. It was confirmed that the method developed from this study is feasible and worth being extensively applied.

1 Introduction

Many highways in Southern China are in urgent need to be reconstructed and expanded to improve their capacities because of the rapidly increasing traffic volumes. In the highway reconstruction and expansion projects, the properties of existing subgrades deteriorate obviously due to the exchange of moisture and heat between subgrades soils and atmosphere [1–4]. For this reason, the treatment of subgrade is a necessary process to improve the service life of the operating quality of the reconstructed highway. Therein the selection of modified materials and design of treatment depth are the main considered contents.

To date, many inorganic binders such as cement, lime and some industrial residues have been widely used in highway engineering to improve the properties of subgrade fillers, and construction technology of these modified materials has been developed well [5–7]. However, the researches on design methods of treatment depth are few, and they mainly focused on the treatment of subgrades consisted of special soils. For example, the *in-situ* expansive force equilibrium method [8], dynamic stress method [9] and atmospheric influence depth method were proposed for expansive soil subgrades [10]. Regarding the subgrades in soft soil areas, the treatment depth can be reduced by adding geotextile reinforced layers [11]. For an existing subgrade made of common soils, the treatment depth is usually determined by experience without theoretical calculations. In most instances, it is confirmed as the thickness of the upper layer or the whole roadbed, which may result in insufficient treatment depth that cannot meet the specification requirements, or an over treatment depth also can lead to a lot of unnecessary material wastes [12, 13]. Therefore, the determination of a properly treatment depth of existing subgrades is a key technique in highway reconstruction and expansion projects.

As a representative property index and design parameter, resilient modulus can reflect the quality of the whole subgrade structure [14, 15]. A principle for determining the treatment depth is to ensure the resilient modulus at the surface of existing subgrades achieves a standard value of specification [16]. Based on the first expressway reconstruction and expansion project of the Lianhua–Zhuzhou Highway in Hunan Province of Southern China, this paper aimed to put forward a method to determine subgrade treatment depth according to the measured resilient modulus at the subgrade surface. Previous field detections revealed that the resilient modulus of this existing subgrade was much lower than 40 Mpa, the specified value in Chinese standards (JTG D30–2015, Specifications for Design of Highway Subgrade; JTG D50–2017, Specifications for Design of Highway Asphalt Pavement). To solve this problem, cement-stabilized soil (CSS) was backfilled to replace the existing subgrade soil to conduct modification. Subsequently, a series of field tests including portable falling weight deflectometer (PFWD) modulus test and Beckman beam deflection test was carried out to evaluate the improved effect of the subgrade with the different number of CSS layers. Thus, the decreasing law of measured deflection was set up from data analysis, and on this bases, the treatment depth can be determined based on the difference between the design deflections and measured ones. Furthermore, according to the relationship between PFWD modulus and the Beckman beam deflection, a method that using the PFWD test to determine the treatment depth of existing subgrades was proposed.

2 Material and methods

2.1 Modified mechanism of CSS

CSS is one of the most widely used modified materials in geotechnical engineering. Its effectiveness of stabilizing soils in a short time is better than lime under the same condition [17]. For this issue, a CSS with a cement content of 7% was used in this project due to the tight schedule of the construction. As is illustrated in Fig. 1, the mechanism of CSS involves a series of physical and chemical reactions. When the cement is mixed into the soil particles, the minerals on the surface of the cement particles will quickly react with the water in the soil for hydrolysis and hydration, generating hydrates such as calcium hydroxide and calcium silicate hydrate, and gradually saturating the water in the soil to form colloids. And then some calcium oxide and silica oxide in cement hydrates continue
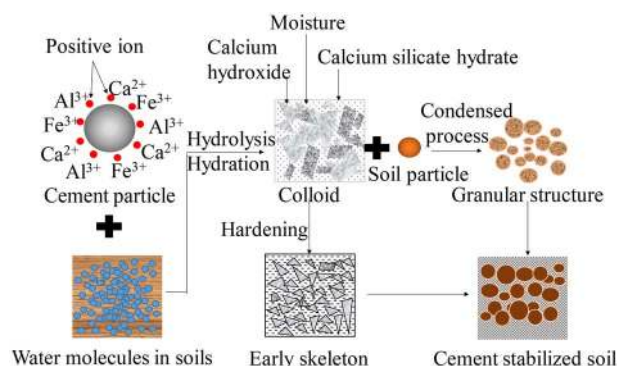
Fig. 1. Strength formation mechanism of CSS

to harden themselves, forming the skeleton of early CSS. The other part of hydrates reacts with soil particles to form soil aggregates and combine with them to form a granular structure. With the deepening of cement hydration reaction, a dense spatial network structure has been formed [18, 19]. As a consequence, the cement and soil particles are interconnected and difficult to distinguish from each other, making the CSS formed. Some laboratory test results showed that CSS has a higher resilient modulus and dry density, but smaller compressibility compared to the unmodified soils [20, 21].

2.2 PFWD test methods

In this study, a series of field tests were carried out to evaluate the properties of the existing subgrade. The compaction degree, plate load test modulus, the Beckman beam deflection, dynamic cone penetrometer (DCP) penetration rate and PFWD modulus were taken as the evaluation indexes of the subgrade performances. The former four were the indexes in Chinese standard to reflect the overall strength of road structures from different views (Field Test Methods for Subgrade and Pavement for Highway engineering). In contrast, PFWD is a new method developed in recent years.

As a portable device used to determine the dynamic modulus of soil, PFWD has gained wide acceptance in the field test for its desirable accuracy and convenience [22]. It can be operated by only one person, and only takes 1-2 min for the detection of one point. PFWD mainly includes a sliding hammer, a loading plate and at least one geophone sensor to detect the deflection at the centre of the plate, as shown in Fig. 2. The working principle is simple. An impulse load is applied to the circular loading plate via a drop weight of

1–15 kN in about 15–20 ms. The response of the loading plate is then measured by a geophone or accelerometer. Therefore, the PFWD modulus (*Ep*) of subgrade layers can be derived from the Boussinesq equation as follows [23]:

$$E_p = \frac{k\left(1 - v^2\right)\sigma r}{\delta} \tag{1}$$

where k is a constant ($k = \pi/2$ for a rigid plate, and $k = 2$ for a flexible plate); δ is the centre deflection; σ is the applied stress; v is the Poisson's ratio; and r is the radius of the loading plate.

There are many studies conducted to evaluate the PFWD test method. The results of the laboratory test performed by [24] showed that its detect depth ranged from 270 to 280 mm depending on the stiffness of the tested materials. Meanwhile, the drop height, loading plate and some other factors can affect the final test results [25–27]. In addition, great efforts have been made to correlate PFWD modulus to the results of other single-location tests, i.e. DCP penetration rate, plate load test modulus and compaction degree [28, 29]. Regarding the performance evaluation of subgrades and pavements, many researchers have conducted considerable comparative tests, and the PFWD test was regarded as an ideal method for quality control during compaction monitoring [30, 31]. The PFWD used in this study was manufactured by YingQi Experimental Instrument Plant of Changsha. The weight of the entire instrument and drop height of the sliding hammer is 10 kN and 85 cm, respectively, the diameter of the load plate is 30 cm.

3 Testing programme

3.1 Detection of the existing subgrade

The selected detection site was located in a highway reconstruction project in Hunan province of Southern China revealed in Fig. 3, Lianzhu Expressway, which was built in 1999 with a length of 78 km. In 2015, it was widened to meet the requirements of increasing traffic volume. The performances of some existing subgrade sections were tested according to the method described below.

3.1.1 Verification tests of the correlation between the Beckman beam deflection (L) and PFWD modulus (E_p). As the Beckman beam deflection test was complicated to operate and time consuming, a substituted method was planned to be proposed first to improve the
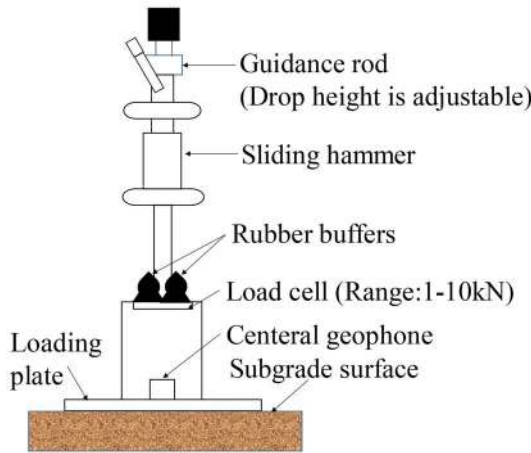
Fig. 2. Structure diagram and the photograph of PFWD

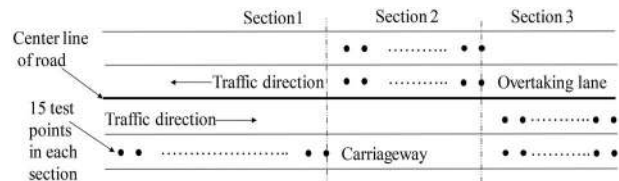

Fig. 3. Tested site location diagram

detection efficiency. In this paper, the PFWD test was preferred considered for its handiness and efficient, but the precondition was that there were high correlations between the measured PFWD modulus E_p and Beckman beam deflection L.

In order to establish the relationship between L and E_p, tentative tests were conducted following these procedures: (i) three subgrade sections of different soils, i.e. section K1105 + 000-K1105 + 100 (clayey gravel), section K1117 + 260-K1117 + 310 (low-liquid-limit sandy clay) and section K1133 + 730-K1133 + 780 (high-liquid-limit silt), were selected as the test objectives; (ii) 15 test points were arranged sequentially on the carriageway or overtaking lane of each section (see

Fig. 4. Layout of test points in the test subgrade sections

Fig. 4), the spacing of these points was set as 5 or 10 m according to the field conditions; (iii) the PFWD test and the Beckman beam deflection test were carried out to obtain the E_p and L.

The measured PFWD moduli and Beckman beam deflections were presented by Fig. 5, it showed that the moduli (E_p) and deflections (L) in different types of soil differed significantly. After the data analyzing, the regression relationships between the PFWD moduli (E_p) and the Beckman beam deflections (L) were shown in Fig. 6. It is observed that when the type of soil is considered, the coefficient of determination (R^2) between the E_p and L is greater than 0.96 in each kind of soils, which indicates that these two indexes are highly correlated. If the type of soil is not considered, the value of R^2 is 0.927, the E_p and L are still highly correlated, which means the Beckman beam test can be replaced by PFWD test, and the Beckman beam deflection (L) also can be calculated out from the PFWD modulus (E_p) based on the relational expression. In addition, to attain more accurate data, the soils of existing subgrade need be classified first, and then the correlation between E_p and L can be established under the condition of the same type of soils.

3.1.2 Comparison test of PFWD moduli at different depths of existing subgrades. To confirming the variation law of
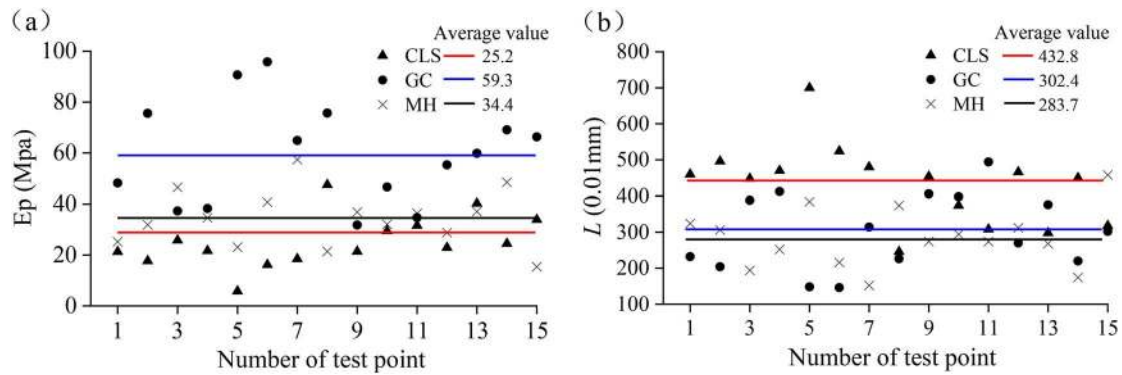
Fig. 5. Test results of measured PFWD modulus and Beckman beam deflectionin (a) and (b)
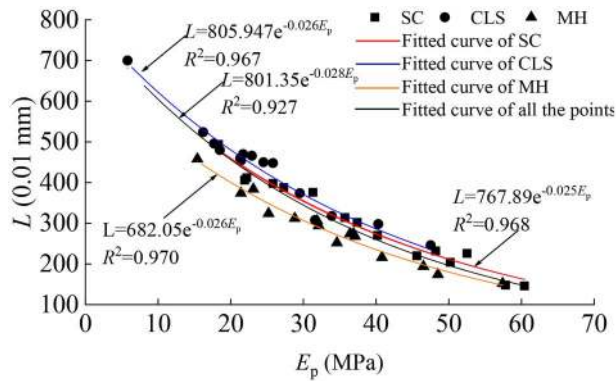

Fig. 6. Correlation between L and E_p of three existing subgrade sectionss

Note: SC = clayey gravel; CLS = low-liquid-limit sandy clay; MH = high-liquid-limit silt

the subgrade modulus at different depths, some comparison PFWD tests were performed on the subgrade section of K1118 + 260–300, where the soil belongs to low-liquid-limit sandy clay. As shown in Fig. 7, the test points were arranged on the centerline of the subgrade with an interval of 10 m. According to the design elevation of the subgrade and pavement structure, the thickness of the entire reconstructed subgrade was 1.2 m. The subgrade was excavated layer by layer, three modulus values were measured at different depths of each test point, i.e. the surface of the subgrade, 0.8 m below the surface and 1.2 m below the surface. The measured PFWD modulus and the calculated deflections were presented in Fig. 7, and the Beckman beam deflection (L) was calculated according to Equation (2):

$$L = 805.947e^{-0.026Ep}(R^2 = 0.967, n = 15) \qquad (2)$$

The test results are proved in Fig. 8, PFWD modulus (E_p) at each test point changed from 16.5 to

18.1 MPa, and the deflection values varied in the range of 508 (0.01 mm) to 540 (0.01 mm). It was found that there is little difference in the measured PFWD moduli of different subgrade depths, and it can be assumed that the deflections are invariant and the entire subgrade is a homogeneous structure. In the practical test, the PFWD modulus (E_p) at the bottom of the subgrade can be substituted by the one at the surface. Thus, the PFWD modulus of the internal subgrade positions can be detected on the surface of the subgrade without excavating, and this conclusion provides a path to greatly reduce the amount of construction work.

3.2 Detection of the stabilized subgrade

After the detection of the existing subgrade, the treatment was started. Subgrade sections in Fig. 3 were treated as the following process: firstly, they were excavated from the pavement surface to the design elevation at the bottom of the new subgrade, and the bottom part was compacted. As the excavated subgrade soils had a high moisture content, the cement was directly mixed into them to form the CSS after stirring. Then the CSS was backfilled layer by layer to build the new stabilized subgrade. It should be noted that each layer needs to be preserved for 7 days to make its strength stabilized.

According to the design scheme of the newly built subgrade, a gravel cushion of 15 cm in thickness was covered on top of the stabilized subgrade. As the whole thickness of the subgrade is 120 cm, the maximum treatment depth is no more than 105 cm. Since the suitable compaction thickness of each layer in the subgrade was confined within a certain range to guarantee the construction quality, the backfilled CSS was identified to be 21-cm thick for each layer and add up to five layers. To investigate the modified
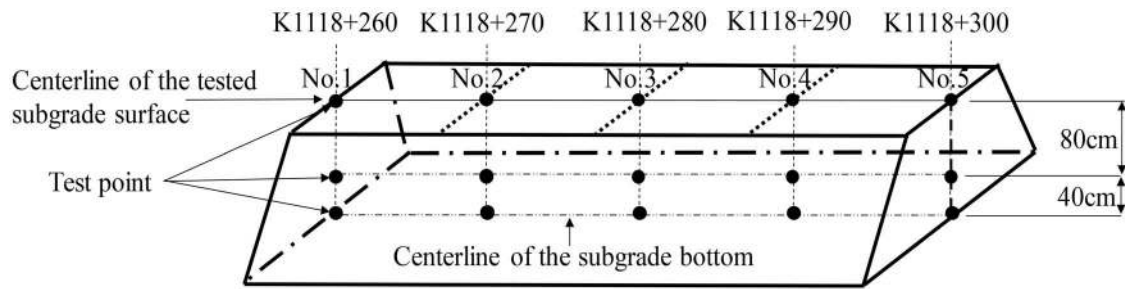
Fig. 7. PFWD tests at different test points of the existing subgrade
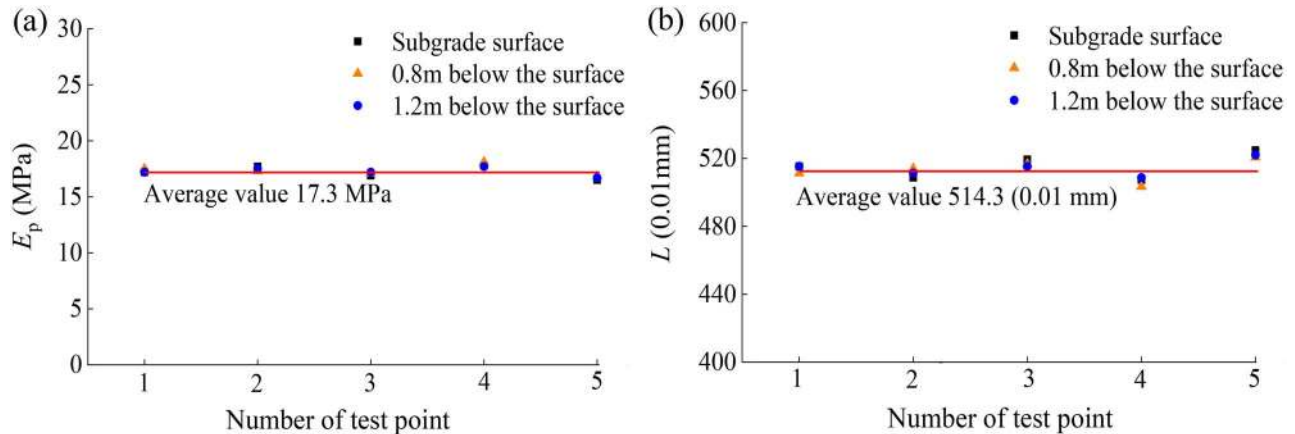

Fig. 8. Test results of the existing subgrade: (a) PFWD modulus; (b) Beckman beam deflection

effect of the treatment, two test points were taken in each subgrade section that previously tested, (i.e. No.1 at K1105 + 055 and No.2 at K1105 + 050 belonged to section 1, No.3 at K1117 + 0270 and No.4 at K1117 + 280 belonged to section 2, No.5 at K1133 + 760 and No.6 at K1133 + 775 belonged to section 3), and PFWD test, Beckman beam deflection test, compaction test, DCP test and plate load test were carried out at the surface of each CSS layer. The variations of four indexes, i.e. Bearing plate test modulus (E_b), Beckman beam deflection (L), compaction degree (K) and penetration rate (PR) were depicted in Fig. 9. It revealed that the improved effect was desirable regardless of the soil type. The stabilized subgrade showed large changes in all the indexes compared to its original state, for instance, the resilient moduli increase by at least 20 MPa with each backfilled stabilized layer added. When one stabilized layers were backfilled, the E_b values at all test points exceeded design value 40 MPa, the compaction degrees reached the design value 96% and the penetration rates decreased to 15 mm/hammer. These three indexes can reach the standard values easily, whereas the deflections did not decrease to meet the design value of 178 (0.01 mm) until four stabilized layers

were backfilled at least. Therefore, the deflection was a most strict indicator, which can be used as a control parameter to ensure the subgrade treatment depth is deep enough.

The average deflection of two tested points was taken for analyzing, and the decreasing law of the deflection with the different numbers of CSS layers was shown in Fig. 10. As an example in the clayey sand section, when the number of the stabilized layers increases, the deflection value decreased and the values of decreased deflection ranged from 92 (0.01 mm) to 336 (0.01 mm). Furthermore, the change rate of the deflections decreased as the number of the stabilized layers increased, and it was smaller in the high-limit-liquid-silt subgrade section than those in others. This suggests that the soil of smaller particle size has a bigger contact surface with cement particles, making them react faster, hence this kind of soil can be modified better in a short time.

To establish the correlation between PFWD modulus (E_p) and the Beckman beam deflection (L) of the stabilized subgrade, the regression relationship is revealed in Fig. 11. The coefficients of determination (R^2) between E_p and L were all greater than 0.9 concerning each test subgrade
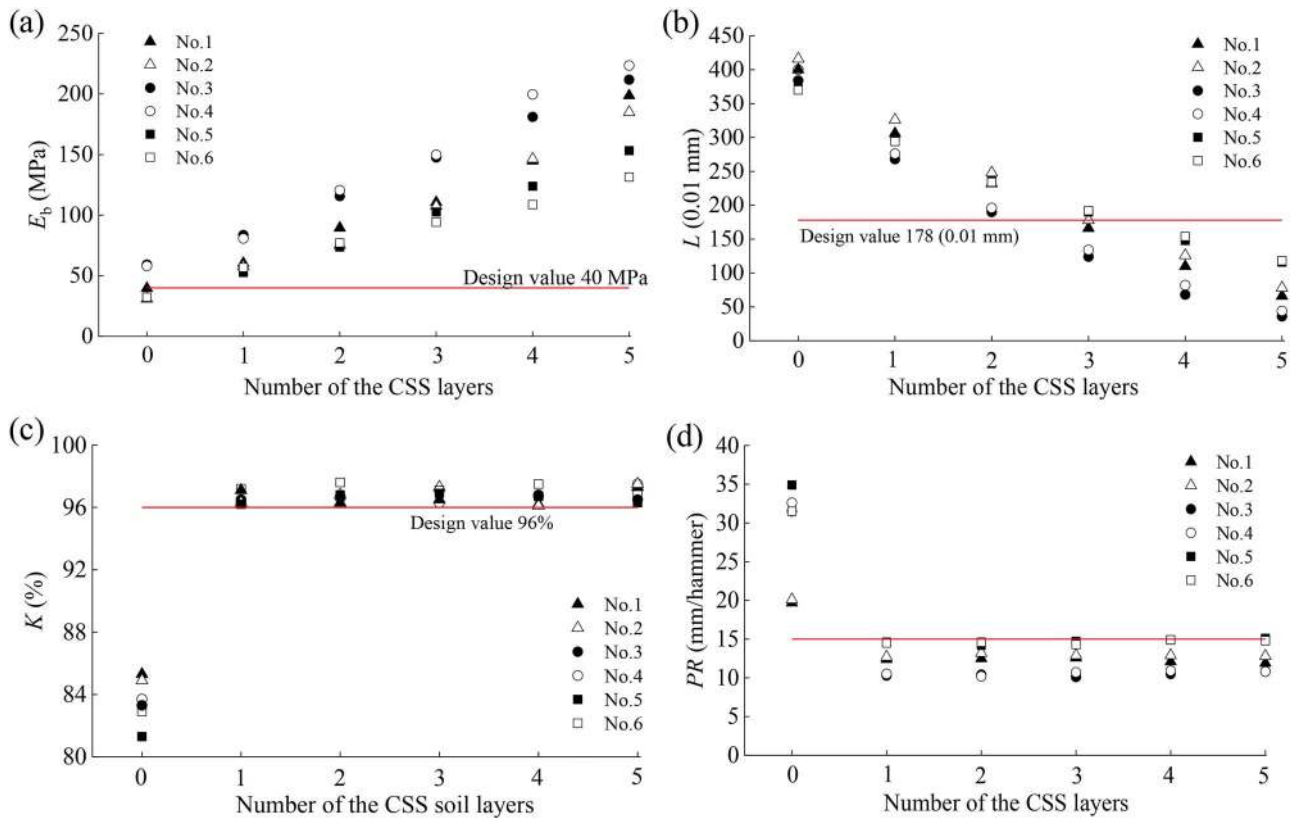
Fig. 9. Variation of four indexes at different CSS layers: (a) Plate load test modulus; (b) Beckman beam deflection; (c) Compaction degree; (d) DCP penetration rate
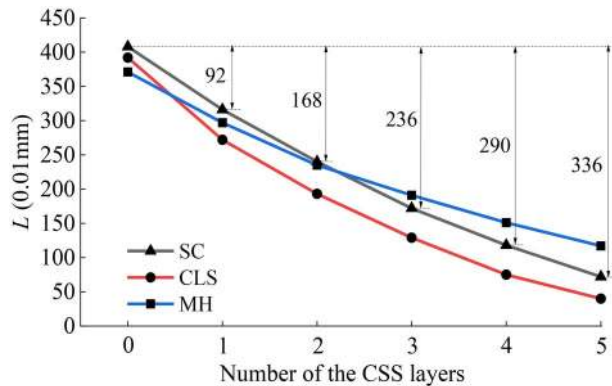

Fig. 10. Variation of average deflections with different number of stabilized layers

Fig. 11. Correlation between L and E_p in the stabilized subgrade

section. When the type of soils was not considered, the coefficients of determination were still greater than 0.7, which indicated that the PFWD can be used to detect the stabilized subgrade instead of the Beckman beam. The deflection (L) can be calculated from the PFWD modulus (E_p) according to the regression relationship, and the latter index can be used as a standard parameter to estimate whether the stabilized subgrade was treated deeply enough. As the design value is 178 mm (0.01), the calculated critical PFWD moduli corresponding to three types
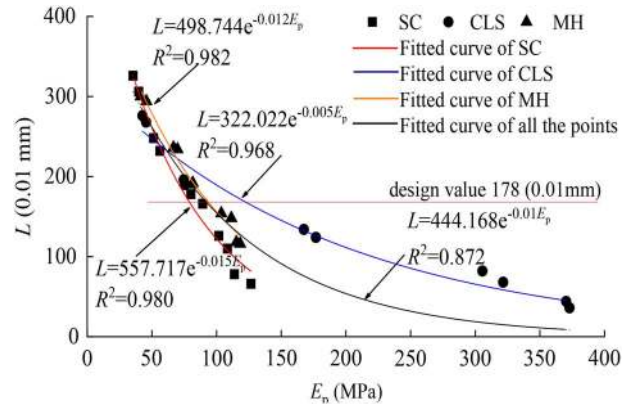
of soils were different: 76 MPa for clayey gravel, 118 MPa for low-liquid-limit sandy clay and 86 MPa for high-liquid-limit silt.

4 Discussion

4.1 Determination method of treatment depth and modified effect analysis

To get the desired processing results, as known from the previous study, the most strict index,

Beckman beam deflection was advised to be the verification index. As the surface deflection of the stabilized subgrade must be less than the design value, the treatment depth can be determined based on the number of indispensable CSS layers. In this project, six schemes considering different treatment depths (i.e. 0, 21, 42, 63, 84 and 105 cm) were proposed for the existing subgrade.

To illustrate this calculation procedure, a case study in the section of clayey sand was given: the deflection at the surface of the existing subgrade was assumed to be 178 (0.01 mm), then the deflection at the bottom was also 178 (0.01 mm) due to the homogeneity of the whole structure proved by Fig. 8. The PFWD modulus can be calculated by the following equation from Fig. 6:

$$L = 767.89 e^{-0.025Ep} (R^2 = 0.968) \qquad (3)$$

According to Equation (3), the PFWD modulus (E_p) corresponding to $L = 178$ (0.01 mm) was 58.5 MPa. In practice, if the measured E_p at the surface of the existing subgrade was greater than or equal to 58.5 MPa, the treatment of the subgrade is unnecessary. In the second situation, it is assumed that the existing subgrade is treated with one layer of CSS, the corresponding treatment depth is 21 cm and the decreased deflection is 92 (0.01 mm) (see Fig. 9). To make the deflection at the surface of the stabilized subgrade less than the design value 178 (0.01 mm), the maximum deflection of the existing subgrade must be less than 270 (0.01 mm) and the corresponding calculated E_p should be greater than 41.8 MPa. Therefore, if the measured E_p at the surface of the existing subgrade changes from 41.8 to 58.5 MPa, then the original subgrade should be treated with one layer of CSS. The corresponding E_p of the subgrade with two, three or four stabilized layers were analyzed in the same way. Additionally, if the measured E_p is no more than 19.8 MPa, the existing subgrade can be should be treated with five layers of CSS. In summary, provided the E_p at the surface of the subgrade was detected out, then the treatment depth of this subgrade can be determined according to Table 1 easily.

To verify the treatment effect, 37 subgrade sections were selected to be treated in this method. The lengths of each section varied from 50 to 150 m, and they were ordered according to the soil category, i.e. No.1-No.2 (clayey sand), No.3-No.9 (low-liquid-limit clayey sand), No.10-No.13 (clayey gravel), No.14-No.30 (low-liquid-limit silty sand) and No.31-No.37 (high-liquid-limit silt). Then the PFWD test was carried out at the surface of these
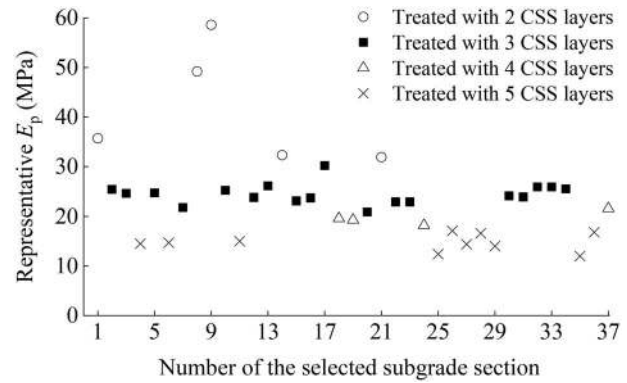

Fig. 12. Representative PFWD modulus of 37 subgrade section

subgrades. For instance, data from one section were listed in Table 2. Test points were arranged on the centerline of the subgrade with an interval of 5 m, and there were 36 measured PFWD moduli (E_p). The representative PFWD modulus of this section E_{pr} can be calculated by Equation 4. (JTG E60–2008, 'Field Test Methods for Subgrade and Pavement for Highway Engineering'). The results of all the E_{pr} were depicted in Fig. 10, and each subgrade section had been labelled how many stabilized layers need to be used in the treatment process according to the value of E_{pr}.

$$E_{pr} = \bar{E}_p - \frac{t_a}{\sqrt{N}} S \qquad (4)$$

where $\overline{E_p}$ is the average value of E_p, t_a is a coefficient related to the number of test points and guarantee rate 0.237, N is the number of test points 36, S is the standard deviation of E_p (Fig. 12).

Then the representative deflections of each subgrade section were figured out by Equation 5 in Fig. 5, and the deflections at the surfaces of the stabilized subgrade (L_b) were measured after the construction of modification, the values of these two indexes were presented by histogram Fig. 13.

$$L_c = 682.05 e^{-0.026E_{pr}} \qquad (5)$$

It can be revealed that all the L_b are less than the design value, indicating that the deflections at the surface of the tested subgrade decreased a lot during the modification process. And it also can be seen in Fig. 12, no matter which type the original subgrade soils belonged to, the ranges of E_{pr} corresponding to the same number of stabilized layers were similar. In this case, the subgrade can meet the design requirement with the least number of CSS layers, making it become an economic treatment scheme.

Table 1. Standard for the treatment depth of the existing clayey sand subgrade

Measured E_p (MPa)	Calculated deflection Lc (0.01 mm)	Difference between the calculated deflection and design deflection ΔL (0.01 mm)	Number of the CSS layer	Treatment depth (cm)
$Ep \geq 58.5$	$L \leq 178$	$\Delta L \leq 0$	0	0
$41.8 \leq E_p < 58.5$	$178 < L \leq 270$	$0 < \Delta L \leq 92$	1	21
$31.8 \leq E_p < 41.8$	$270 < L \leq 346$	$92 < \Delta L \leq 168$	2	42
$24.7 \leq E_p < 31.8$	$346 < L \leq 414$	$168 < \Delta L \leq 236$	3	63
$19.8 \leq E_p < 24.7$	$414 < L \leq 468$	$236 < \Delta L \leq 290$	4	84
$E_p < 19.8$	$L > 468$	$\Delta L > 290$	5	105 tv

Table 2. Test results of the No. 31 section

Section No.	E_p (MPa)	E_{pr} (MPa)6.0pt1,96.73936pt	Number of CSS layer	Treatment depth (m)
31	22.3, 24.9, 21.1, 22.9, 20.7, 29.2, 26.9, 22.4, 27.9, 23.0, 28.4, 20.8, 20.8, 19.8, 30.4, 22.7, 25.5, 21.2, 22.6, 23.3, 23.6, 25.6, 29.4, 20.8, 27.9, 28.2, 27.5, 27.8, 25.2, 29.8, 20.7, 29.2, 20.3, 27.3, 20.5, 29.7	23.9	3	0.63
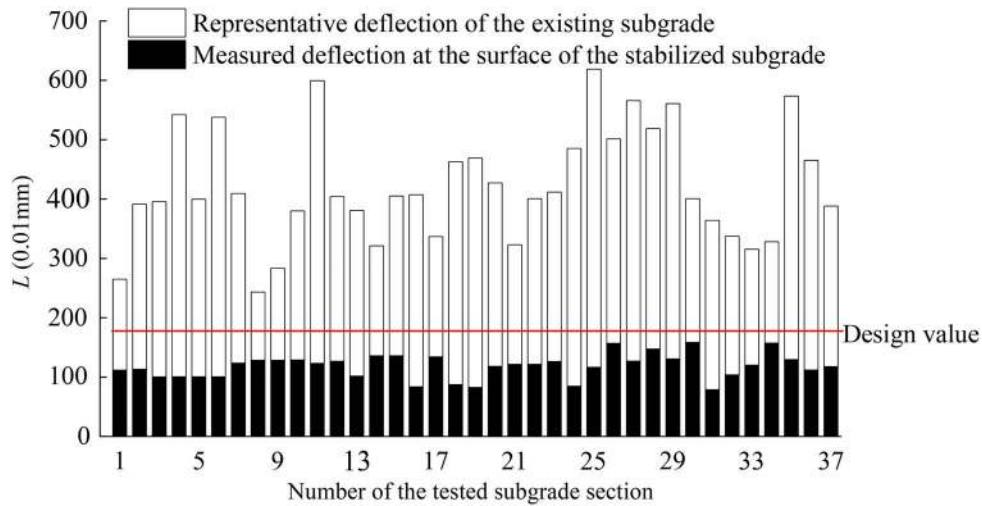
Fig. 13. Deflection variation of the tested subgrade sections by modifying with CSS

4.2 Analytical solution analysis of the treatment subgrade model

In the Chinese standard 'Specifications for design of highway Asphalt Pavement (JTG D50–2017)', the model used to calculate the mechanical index of the pavement structure is simplified into the elastic layered continuous system under the double circle uniform vertical load. Thus, the deflection of the subgrade surface also can be calculated by this method in a two layers elastic and symmetry model, which was consisted of the top layer and bottom layer shown in Fig. 14. The existing subgrade and foundation were seen as the bottom layer consisted of one kind of material, and the stabilized layer was assumed as the top layer made of another kind of material. The calculated method was shown in Equations (6) and (7) [32]:

$$L = -\frac{(1 + \mu 1) p\delta}{E_1} \int_0^\infty \{[A_1 + (2 - 4\mu_1) B_1 + C_1 - (2 - 4\mu_1) D_1]\} J(m) J_0 \left(\frac{r}{\delta}x\right) \frac{dx}{x} \quad (6)$$

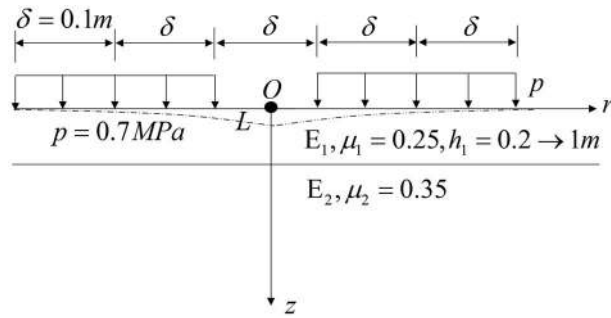$$J(m) = \frac{2^{m-1}\Gamma(m + 1)}{X^{m-1}} J_m(X) \quad (7)$$

Fig. 14. Simplified calculation model

Fig. 15. Analytical results of the subgrade deflection with stabilized layers

where A_1, B_1, C_1, D_1 are the coefficients of the boundary condition of the top layer; P is the load value; δ is the radius of the loading area; $r = 1.5\delta$; E_1 and E_2 are the elastic modulus of two layers; μ_1, μ_2, are Poisson ratio of two layers; $J_x(m)$ is the Bessel function; $\Gamma(m+1)$ is the Euler integral formula; m is the coefficient associated with the load form, and it was taken 1 when the circle loading is uniformly distributed.

The analytical results of the subgrade surface deflection under different conditions of E_1 and E_2 were presented in Fig. 14. It was shown that the deflection decreased with the stabilized layer thickness increased, which was consistent with the changing law of the curves in Fig. 9. The two effect factor E_1 and E_2 were analyzed qualitatively with No.3 curve ($E_1 = 500$, $E_2 = 40$) being taken as the reference. When E_1 was increased or decreased 100 Mpa and E_2 was unchanged, the corresponding No.2 and No.4 curves were near to the No.3 curve. In contrast, when the E_2 changed 10 Mpa and E_1 was unchanged, the corresponding No.1 and No.5 curves were far away from the referenced curve. Thus, it can be estimated that the effect of the bottom layer modulus (E_2) to the subgrade surface deflection is much more than that of the top layer (E_2) (Fig. 15).

5   Conclusions

Based on the reconstruction project of Lianhua–Zhuzhou Highway, this paper put forward a method to determine the subgrade treatment depth economically and properly, and it was proved effective in the application. The following conclusions can be drawn by the series of tests in the modification process.

There were considerable good correlations between PFWD modulus and the Beckman deflection in the existing subgrade and the stabilized one, the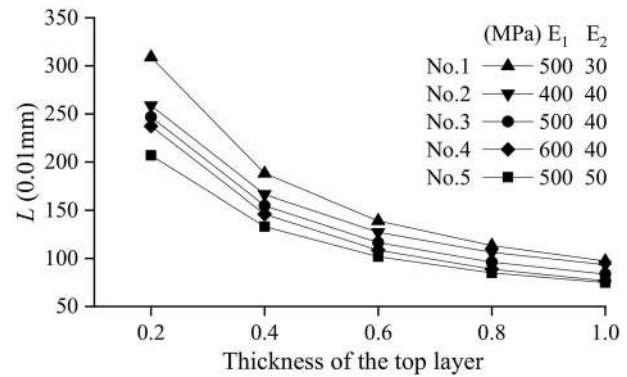se two indexes can be converted each other from the established relational expression. As it is convenient operating and efficient in field testing, PFWD modulus is more suitable to be used as the determination index compared to the Beckman beam deflection. The measured PFWD modulus at the surface of the existing subgrade can be used directly to estimate the number of the required CSS layers, this will greatly improve the efficiency of the whole engineering.

By series of the field tests, it was found that the measured PFWD moduli of the same location at different depths of the existing subgrade were identical, thus the whole subgrade can be seen as a homogenous structure, and the PFWD modulus at the bottom of subgrades can be detected out without excavating.

For different subgrade sections made of the different the soils, the decreasing law of the deflection was not the same, indicated that the modification effect is associated with the type of the subgrade soil.

In the analytical solution of the double layers model, the effect of the elastic modulus of the bottom layer to the subgrade surface is much more than that of the top layer. The elastic modulus of the existing subgrade is still a key index that should be studied emphatically rather than that of the modified materials.

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