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In Situ Assessment of Pavement Subgrade Using Falling Weight Deflectometer

Reference

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ABSTRACT

The stiffness modulus and density of pavement subgrade contribute significantly to the long-term performance of a pavement structure. Subgrade functions primarily as a support for road pavement structures. Poor performance of the pavement structure is often a result of a lack of quality control during the construction of the subgrade layer. This paper presents a case study in which a falling weight deflectometer (FWD) test was used to evaluate whether the subgrade layer had achieved the required design stiffness modulus and density during construction. The characteristics of the FWD deflection basins were analyzed and the stiffness modulus was back-calculated using the CIRCLY5 pavement analysis program. The problems associated with FWD testing directly on subgrade are discussed, and an appropriate test load is proposed. Deflection-based models are developed by relating the FWD center deflection with the in situ stiffness modulus and density of the subgrade layer. A dynamic cone penetrometer test was carried out to determine the in situ stiffness modulus, and the results are compared with the back-calculated stiffness from CIRCLY5.

Keywords

pavement subgrade, falling weight deflectometer, dynamic cone penetrometer, stiffness modulus, compaction density, CIRCLY5

Introduction

Quality assurance in compaction control during subgrade construction is vital to the long-term performance of the pavement foundation. Appropriate in situ compacted soil density, soil bearing capacity, and shear strength are essential for quality assurance in subgrade construction because the long-term performance of the pavement structure is directly related to the physical properties and condition of the pavement foundation. An unstable pavement foundation will present

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problems in providing adequate support for traffic loads. A uniform, densely and properly compacted subgrade will provide a satisfactory foundation on which the pavement layer can be constructed. Uniform compaction is essential in achieving a uniform condition during subgrade construction and thereby ensuring uniform pavement performance.

In most highway projects, the volume of compacted fill is large and the length of the roadway stretches over a great distance. The need for an accurate and reliable subgrade characterization to ensure adequate quality control of compaction during construction is obvious. The in situ density test, California bearing ratio (CBR) test, and plate bearing test are presently employed to determine whether compaction and design requirements are being achieved. The current methods of subgrade compaction control might not be satisfactory because in most cases only the density and moisture content of the pavement foundation are tested. Moreover, the plate bearing test requires complicated test work, and the site assignment is usually very costly because a heavy load is needed for reaction force during the test. The time taken to complete a single plate bearing test point is also rather long. Close intervals in testing are not achievable because of the cost and time factors. Because of the deficiencies in the current testing and analysis methods, there is a research need to implement an alternative method of compaction testing during subgrade construction.

This paper presents a case study of research carried out for the development of a quick and economical method of assessing the in situ stiffness and density of pavement subgrade using a falling weight deflectometer (FWD). Presently, the use of the FWD deflection test for quality control in subgrade construction is limited, and there is a general absence of evaluation criteria and an appropriate methodology for analysis of the FWD data. This prompted the need to initiate a study to expand the usage of the FWD in verifying the stiffness and density of pavement subgrade in both road rehabilitation and new construction works. The study was carried out at a test site near Kuala Lumpur International Airport (KLIA) in Malaysia. The characteristics of the FWD deflection bowls were analyzed and the stiffness modulus was back-calculated using the CIRCLY5 [1] pavement analysis program. A simplified subgrade model has been proposed for use in assessing the pavement subgrade layer. Mathematical models were developed for predicting the stiffness modulus and density of the subgrade using the FWD deflection data. A dynamic cone penetrometer (DCP) test was carried out to determine the in situ subgrade stiffness modulus, and the results were compared with the back-calculated stiffness from CIRCLY5.

FWDs are widely used by highway agencies for network-level deflection surveys to assess the rate of pavement deterioration and determine the timing for rehabilitation. Considerable research has been devoted to the study of the application of FWD test results for pavement structural evaluation and for

back-calculation of layer moduli of in-service pavements. A large collection of technical papers pertaining to the subject can be found in the publications edited by Bush and Baladi [2] and Tayabji and Lukenen [3].

FWD tests have been performed on an unpaved section of test pavement in The Netherlands by Sweere and Galjaard [4] for in situ determination of the elastic stiffness of granular base course. The load of the FWD was set at 20 to 30 kN, depending on the response of the tested layers to the impact of the FWD. Chai and Asmaniza [5] used an FWD to determine the in situ stiffness of cement stabilized granular base layers. Results from the FWD were also used to verify the design parameters for the stabilized base layer, and an empirical relationship between the deflection and the unconfined compressive strength of the cement stabilized layer was developed in the study. The FWD was found to be useful for the structural assessment of the stabilized base layer prior to the placement of asphalt layers.

There is a general absence of evaluation criteria for FWD deflections on top of foundation layers [6]. In Queensland, Australia, heavy-duty pavement construction [7] requires a working platform below the lowest pavement layers to provide protection to the underlying subgrade materials. The working platform comprises granular material with a minimum CBR value of 45 %, stabilized with a minimum of 2 % cement. PSTS101 [8] specifies that FWD testing should be undertaken during construction on top of the working platform layer. Grobler and Taylor [6] performed FWD testing on the working platform to ensure that the desired structural integrity of the foundation layer was achieved during construction. Several state road authorities in Australia have developed methods for estimating subgrade CBR values from FWD deflection data [9]. These methods are generally empirically based and can provide indicative values for certain pavement types such as unbound granular pavements with thin bituminous surfacing [10,11]. The deflections recorded at sensor D₉₀₀, located 900 mm from the FWD load, are used in the models.

A literature review was carried out on the use of FWD testing directly on subgrade, and it was found that FWDs have been employed for assessing the subgrade layer by Abe et al. [12], Uddin [13], Shahid et al. [14], Chai et al. [15], Rahim and George [16], Loizos et al. [17], Stubstad [18], and George [19]. Abe et al. [12] used an FWD to evaluate the bearing capacity of both base course and subgrade in Japan. They have introduced FWD measurement for pavement thickness designs using soft subgrade such as volcanic cohesive soil. The study showed that the FWD is applicable not only for pavement performance evaluation but also for quality control during construction. Uddin [13] indicated that conducting FWD deflection tests on subgrade is problematic and the data are difficult to interpret for routine pavement designs. Rahim and George [16] concluded that the moduli measured from FWD tests conducted directly on the subgrade were in good agreement with the

laboratory-measured M_r . Another research study was carried out by Stubstad [18] to determine whether the FWD can be used effectively to assist in the quality control/quality assurance process during pavement construction. The long-term pavement performance study in the United States provided the data needed to accomplish the research. The study found that the FWD test results on unbound materials were reasonably well related to material properties determined from laboratory and other in situ field tests. The FWD test results provided data that can be used with confidence to estimate material properties (mainly stiffness or moduli and their variations) at each interface during new and reconstructed pavement construction. George [19] conducted a study to investigate the feasibility of using an FWD for direct testing of subgrade with the objective of deriving the resilient modulus via a correlation between the FWD modulus and the laboratory-measured M_r . Chai and Faisal [20] used an FWD to characterize a subgrade constructed with residual soil in a tropical environment. The stiffness modulus and density of a pavement foundation were determined using an FWD during construction. Empirical models have also been developed for predicting the undrained shear strength of the subgrade layer using an FWD [15].

ENGINEERING PROPERTIES OF SUBGRADE SOIL

The soil material used for subgrade construction consisted of residual soil derived from a granitic formation near the KLIA test site. The granite is weathered, and a wide spectrum of weathering profiles is evident from the bore log results obtained from the site. The granite is overlain by a thick layer of residual soil exceeding 60 m. The subgrade soils are described as completely weathered granitic residual soils and are classified as Grade VI in the British Standard Scale of Weathering Grades of Rock Mass [21]. The residual soils are described as yellowish brown in color and medium to very stiff in consistency. The soil is predominantly silty clay with a sand content of 43 % and silt and clay contents of 23 % and 18 %, respectively. The Atterberg limits are the plasticity index (32 %), liquid limit (64 %), and plastic limit (32 %). The optimum moisture content and maximum density are 15.5 % and 1.80 mg/m³, respectively. According to the AASHTO Soil Classification System [22], the soil is classified as A-7-5 and is described as silty clay.

TESTING PROGRAM

FWD testing was carried out at a test site on a road embankment near KLIA. The nondestructive testing device was a Dynatest Model 8000 FWD. The site consisted of three test sections each measuring 100 m by 6 m. The test sections are referred to herein as test section 1 (TS1), test section 2 (TS2), and test section 3 (TS3). The subgrade was prepared with granitic residual soil as described in the previous section, and each layer was laid with a loose depth not greater than 200 mm and compacted with a 12-metric-ton roller. Compaction sequences

of 2, 6, and 10 roller passes were used for TS1, TS2, and TS3, respectively. The FWD deflection measurements and DCP tests [23] were taken at 20-m intervals along the three test sections, and the tests were repeated at all the compaction sequences. There were a total of 15 FWD and 15 DCP test points spaced at 20 m along the test sections. The maximum soil density and the optimum moisture content were determined in accordance with AASHTO T-180-01 [24] and BS 1377-4 [25]. The sand cone replacement method [23] was utilized to verify the density of the compacted subgrade layers.

The FWD geophones were placed at 0 mm, 300 mm, 500 mm, 750 mm, 1050 mm, 1350 mm, and 1650 mm from the loading position to measure the full subgrade deflection basin. Preliminary tests were carried out using an FWD impact load of 40 kN and a contact pressure of 550 kPa at the three test sections. The deflection under the 300-mm diameter plate in all the test sections was greater than 2500 μm (2.5 mm) and exceeded the sensor limit of 2000 μm (2.0 mm). Plastic deformation on the subgrade was observed under the test plate using this impact load. In view of the problems, the test load was changed to 10 kN (contact pressure of 135 kPa), reflecting the stress imposed on the subgrade layer under actual traffic loading on the finished pavement. A check was carried out using a Spirit Level device to ensure that the surface of the subgrade was smooth and even prior to the test. Unevenness of the subgrade layer can cause improper seating of the impact load and sensor errors in recording the deflection. Prior to the test, it was also important to ensure that loose gravel materials were not present on the subgrade surface. In the section where the subgrade surface was found to be even and met the testing requirements, the FWD test was then allowed to proceed.

DATA ANALYSIS

A profile of the 15 deflections at the center of the FWD load (D_0) for the three test sections is presented in Fig. 1. The deflection profiles indicate the variation of the structural condition of the subgrade layer when compacted to different degrees of compaction. As the degree of compaction increased, the deflection (D_0) decreased. For TS1, D_0 varied from 1045 μm (1.045 mm) to 1119 μm (1.119 mm) at two compaction passes. A reduction in D_0 values was recorded at TS2 at six compaction passes, and the range of D_0 was from 504 μm (0.504 mm) to 608 μm (0.608 mm). A smaller deflection D_0 was observed at TS3 when 10 compaction passes were applied to the subgrade layer. The average deflection recorded at TS3 was 340 μm (0.340 mm). The deflection basins for test point 1 in TS1, test point 6 in TS2, and test point 11 in TS3 are presented in Fig. 2.

A simplified subgrade (SS) model was proposed for analyzing the FWD deflection data obtained from the three test sections. The subgrade model as depicted in Fig. 3 consisted of a two-layer system. The two layers were subgrade layer 1 and subgrade layer 2 with infinite depth. The stiffness moduli of

FIG. 1 Profiles of FWD deflection for the test sections.

compacted subgrade layers 1 and 2 were determined by applying a 10-kN load (contact pressure of 135 kPa). The maximum deflection (D_0) underneath the center of the load was used to compute the subgrade surface modulus using Boussinesq's equation [26] as shown in Eq 1. The subgrade surface modulus at a distance r from the impact load was computed using Eq 2.

$$(1) \quad E_0(0) = \frac{2 \times (1 - \nu^2) \times R \times \sigma_0}{D_0}$$

$$(2) \quad E_0(r) = \frac{(1 - \nu^2) \times R^2 \times \sigma_0}{r \times D_r}$$

where:

$E_0(0)$ = subgrade surface modulus at the center of the load, MPa,

$E_0(r)$ = subgrade surface modulus at a distance r , MPa,

ν = Poisson's ratio (0.45),

R = radius of the plate, mm,

FIG. 2 FWD deflection basins for TS1, TS2, and TS3.

σ_0 = contact pressure, kPa,

r = distance from the center of the loading plate, mm,

D_0 = deflection underneath the center of the load, mm, and

D_r = deflection at distance r , mm.

The surface modulus was computed using the deflection recorded at sensors D_0 , D_{300} , D_{500} , D_{750} , D_{1050} , D_{1350} , and D_{1650} . The profiles of the surface modulus for test points 1, 6, and 11 are shown in Fig. 4. In all cases, the surface modulus increased at a distance from the impact load. An explanation for this observation is the nonlinearity of the subgrade, which is evidenced by the variation of the surface modulus with the distance from the load. As the stress level decreases at a distance, the surface modulus increases. The variation was significant for TS1 with two compaction passes. As the densification of the subgrade layer increased with 10 compaction passes, the increase in the surface modulus was less profound.

CIRCLY5 [1], a pavement analysis computer program, is an integral component of Austroads [9,27] pavement design. CIRCLY5 was used to back-calculate the stiffness modulus of the subgrade layers by matching the FWD deflection with that generated by the program. Modeling of the subgrade deflection was performed using the SS model under the same loading condition. The subgrade layer was modeled as an anisotropic material. The surface modulus computed using Boussinesq's equation and the back-calculated stiffness modulus from CIRCLY5 were verified using in situ DCP tests. The in situ stiffness value can be computed using the DCP penetration count in millimeters per blow with the following equation [28]:

$$(3) \quad E_{DCP} = 2224 * DCP^{-0.996}$$

where:

E_{DCP} = subgrade stiffness modulus, MPa, and

DCP = dynamic cone penetrometer count, mm/blow.

DISCUSSION OF RESULTS

The deflection basins generated by the FWD at the three test sections at different degrees of compaction are presented in Table 1. The computed surface modulus and the back-calculated stiffness modulus of the subgrade layers on TS1, TS2, and TS3 are presented in the last two columns of the table. The FWD deflections presented in the table are 50th percentile and 90th percentile values. The 50th percentile deflection parameters represent the median values. The 90th percentile deflection parameters show that only 10 % of the deflections were higher than the indicated deflection. For TS1, the mean D_0 deflection was 1082 μ m (1.082 mm) and the 90th percentile value was 1109 μ m (1.109 mm). The 90th percentile values for TS2 and TS3 were 607 μ m (0.607 mm) and 392 μ m (0.392 mm), respectively. For D_{300} , the deflection was relatively small and varied from 70 μ m to 160 μ m. For D_{450} , the deflection varied from 31 μ m to 36 μ m and was nearly identical despite the increase in the compaction

FIG. 3

Simplified subgrade model.

effort. The same trends were observed for sensors D_{750} , D_{1050} , D_{1350} , and D_{1650} . One reason for these consistently small deflections is the dynamic effect of the FWD load, which influences mainly the subgrade material near the impact load at the time of contact. Care must be exercised in back-calculating the stiffness modulus by attempting to match all the deflections at sensor distances greater than 300 mm. If these sensors' deflections are matched, the back-analyzed stiffness modulus for subgrade layer 1 will be unreasonably low, and that for subgrade layer 2 will be extremely high. As a consequence, the back-analysis will result in large errors. Moreover, the FWD test was conducted directly on subgrade layer 1, which was constructed on top of subgrade layer 2, made of similar soil material and with similar compaction specifications. The center deflection D_0 is the indicator of the overall structural response of subgrade layer 1 immediately underneath the test plate. As such, D_0 is the

deflection parameter that needs to be matched in the back-analysis.

Table 1 shows that reasonably good agreement was achieved between the surface modulus derived from Boussinesq's equation and the back-analyzed stiffness modulus from CIRCLY5, especially the stiffness modulus at the 50th percentile of the deflections. A large deviation ($> 20\%$) is observed at TS1 for the deflections at the 90th percentile value. For TS1, the surface modulus was computed as 32.8 MPa and 32.0 MPa for the 50th and 90th percentiles of deflection, respectively. The surface modulus for TS3 varied from 89.4 MPa to 124.7 MPa, and the 50th and 90th percentile values were computed as 104.5 MPa and 90.6 MPa, respectively.

The results for the sand cone replacement (SCR) relative density indicating the degree of compaction and the DCP tests are presented in **Table 2**. The SCR field tests conducted at the three test sites provided the compacted density values necessary for the relative density (or degree of compaction) calculation. The degree of compaction achieved after 10 compaction passes was 98 % on average. The DCP results validated the surface modulus and the back-calculated stiffness modulus as presented in **Table 1**. A similar trend was observed in the DCP tests, where the average in situ stiffness modulus increased from 32.3 MPa at TS1 to 107.6 MPa at TS3.

The correlation between the surface modulus obtained using Boussinesq's equation and the in situ stiffness moduli obtained with the DCP device is presented in Eq 4. The correlation has R^2 and root mean square error (RMSE) values of 0.98 and 3.28, respectively. **Figure 5** depicts the correlation. The correlation between the stiffness moduli obtained from back-calculation using CIRCLY5 and the in situ stiffness moduli obtained with the DCP device is shown in Eq 5. The correlation has R^2 and RMSE values of 0.99 and 2.35, respectively. The relationship is depicted in **Fig. 6**. Hence, the $E_{\text{Back}}-E_{\text{DCP}}$ model has a slightly higher R^2 value and a smaller RMSE value than the

FIG. 4 Surface moduli for test points 1, 6, and 11.

TABLE 1 Surface modulus and back-calculated stiffness modulus from FWD.

Test Section	Statistics (Percentile)	Deflection, μm or $\text{mm} \times 10^{-3}$ Sensor Location							Surface Modulus, MPa	Back-analyzed Stiff Modulus, MPa
		D_0	D_{300}	D_{500}	D_{750}	D_{1050}	D_{1350}	D_{1650}		
Test site 1 (two roller passes)	50th	1082	143	32	14	12	7	5	32.8	30.0
	90th	1109	160	35	16	12	10	8	32.0	25.0
Test site 2 (six roller passes)	50th	563	89	33	18	13	11	8	63.1	60.0
	90th	607	97	36	20	15	14	9	58.5	55.0
Test site 3 (10 roller passes)	50th	340	70	31	17	12	8	6	104.5	100.0
	90th	392	77	34	19	13	10	7	90.6	90.0

E_s - E_{DCP} model. This indicates that the back-calculated stiffness modulus from CIRCLY5 provides a better fit with the in situ stiffness data derived from the DCP.

$$(4) \quad E_s = 0.81 * E_{\text{DCP}} + 8.75$$

$$(5) \quad E_{\text{Back}} = 0.989 * E_{\text{DCP}} - 5.68$$

where:

E_s = surface modulus, MPa,

E_{Back} = back-calculated stiffness modulus, MPa, and

E_{DCP} = in situ stiffness modulus derived from DCP testing, MPa.

The relationship between the deflection D_0 and the surface modulus derived via the forward calculation of the surface modulus using Boussinesq's equation is shown in Fig. 7. The relationship is given in Eq 6.

$$(6) \quad E_s = 28999 * D_0^{-0.977}$$

where:

E_s = surface modulus, MPa, and

D_0 = deflection at the center of the load, μm or $\text{mm} \times 10^{-3}$.

From the results of the back-calculation using CIRCLY5, a mathematical relationship between the deflection D_0 and the in situ stiffness modulus was derived from the study, and it is depicted in Fig. 8. The upper and lower 95 % statistical confi-

dence levels are plotted in the graph. The relationship is given as follows:

$$(7) \quad E_s = 193863 * D_0^{-1.286}$$

where:

E_s = subgrade stiffness modulus, MPa, and

D_0 = deflection at the center of the load, μm or $\text{mm} \times 10^{-3}$.

The results showed that subgrade deflection improved remarkably as the stiffness modulus of the subgrade increased. The deflection (D_0) decreased from 1000 μm to 400 μm as the stiffness modulus increased from 30 MPa to 88 MPa. The E_s - D_0 relationship is a useful and quick method for determining the in situ stiffness modulus of the subgrade layer during construction. In this manner, the design parameter can be confirmed during the construction stage to ensure that the pavement design intent is fulfilled.

Another observation that can be made from this study is that the density of the compacted subgrade is also related to the FWD deflection D_0 . The deflection recorded at D_0 improved from 1119 μm to 285 μm and it was significantly influenced by the densification of the subgrade layer. The density- D_0

TABLE 2 DCP and density results.

Subgrade Description	Test Site 1	Test Site 2	Test Site 3
Layer 1			
Layer thickness, mm	200	200	200
Compaction roller passes	2	6	10
Compaction density, mg/m^3	1.51–1.54	1.68–1.72	1.75–1.79
Degree of compaction, %	83–85	93–95	97–99
Range of DCP counts, mm/blow	69–75	27–36	17–22
Range of E_{DCP} , MPa	30–32	63–84	105–128
Average E_{DCP} , MPa	32.3	74.0	107.6
Layer 2			
Layer thickness, mm	Semi-infinite	Semi-infinite	Semi-infinite
Range of DCP counts, mm/blow	26–28	27–36	16–20
Range of E_{DCP} , MPa	80–86	82–94	112–135

FIG. 5 Surface modulus versus in situ stiffness modulus from DCP.

FIG. 6 Back-calculated stiffness modulus versus in situ stiffness modulus from DCP.

relationship is depicted in **Fig. 9**. In TS2, a 95 % degree of compaction was said to have been achieved when D_0 recorded a reading of about 450 μm .

CONCLUSIONS AND RECOMMENDATIONS

An essential detail of the in situ evaluation of pavement subgrade using an FWD has been presented in this paper. The problems associated with excessive deformation with FWD testing directly on subgrade have been highlighted, and the study recommended that the test load be reduced to 10 kN (contact pressure of 135 kPa), reflecting the stress imposed on the subgrade layer under actual traffic loading on the finished pavement. The study indicates that an FWD can be effectively used for the characterization of the quality of the subgrade during construction.

FIG. 7 Surface modulus versus deflection D_0 . **FIG. 8** Back-calculated stiffness modulus versus deflection D_0 .

Deflection-based subgrade characterization models have been developed by relating the FWD center deflection with the in situ stiffness modulus and density of the subgrade layer. The results show that forward calculation of the surface modulus using Boussinesq's equation and back-calculation using CIRCLY5 provide a consistent prediction of the subgrade stiffness modulus. A simplified subgrade (SS) model has been proposed for use in back-calculating the stiffness modulus. The SS model can be modeled as a one-layer system when a 95 % degree of compaction has been achieved because at this level of compaction, the stiffness modulus values of layers 1 and 2 are nearly the same.

The DCP results validated the surface modulus and the back-calculated stiffness modulus. The in situ stiffness modulus obtained from the DCP agreed reasonably well with the back-calculated stiffness modulus from CIRCLY5. Another observation that can be made from this study is that the deflection

FIG. 9 Density of subgrade versus deflection D_0 .

recorded at D_0 is influenced by the densification of the subgrade layer. It was concluded that a 95 % degree of compaction or in situ stiffness modulus of 75 MPa could be said to have been achieved when D_0 recorded a reading of about 450 μm .

The correlation between the in situ stiffness modulus and the deflection developed in the current study is for subgrade constructed with silty clay (AASHTO Type A-7-5). Prior to full-scale use of the deflection models for quality control during construction, it is recommended that the models be calibrated for different subgrade soils encountered at the site. A similar subgrade trial test is recommended for developing site-specific stiffness modulus–deflection and density–deflection correlations for particular subgrade constructions.

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