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Issues pertaining to Backcalculation of Stiffness Modulus in Flexible Pavements with Highly Nonlinear Subgrade Materials

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Abstract. A study in South East Queensland has found that a large percentage of thin surfaced flexible pavements exhibiting moderate to highly nonlinear subgrade behavior. The nonlinearity effects are major problems encountered in back-analysis of this group of pavements and it can yield back-calculated results with superficially high subgrade stiffness modulus and extremely low stiffness modulus at the road base layer. In other cases, the back-calculation yields very high asphalt stiffness and very low subgrade stiffness modulus. Back-analysis of the falling weight deflectometer bowls can be used to estimate the stiffness modulus of the subgrade from software packages such as EFROMD2. Occasionally, EFROMD2 does not converge mainly because of the certain actual material behavior cannot be handled by the elastic layer model in CIRCLY that is used in EFROMD2. A research has been carried out to analyse the back-calculated results of EFROMD2 and CIRCLY5 for pavement structures that possess highly nonlinear subgrade behavior. The study shows that the EFROMD2 computer program over predicts the asphalt stiffness and under predicts the subgrade stiffness. On the contrary, CIRCLY5 program generates back-calculated results with very high subgrade stiffness and very low stiffness modulus in the road base layer. The issues pertaining to the back-calculation of flexible pavements that possess highly nonlinear subgrade behaviour is presented. A simple approach to compute the degree of subgrade nonlinearity will be introduced.

Keywords: Nonlinear subgrade model, highly nonlinear subgrade materials, Back-calculation, stiffness modulus, thin surfaced flexible pavements

Introduction

Modelling of structural integrity of pavements is now an important part of road asset management because many pavement performance models are related to pavement strength. Falling Weight Deflectometer (FWD) is used by highway agencies worldwide for network level deflection survey for assessing the rate of pavement deterioration and to determine the timing for rehabilitation. Pavement surface deflection measurements provide valuable information on the structural condition of pavement systems. Back-calculation of layer properties including pavement layer moduli from FWD surface deflection measurements plays a major role in the structural evaluation of pavements. From the back-calculated layer moduli, the critical stresses and strains of the pavement structure can then be determined. The deterioration of a pavement is caused by the stresses and strains in the different layers and the remaining life of the structure can be predicted from this information.

Sprayed seal and thin asphalt pavements are the most commonly used by State and Local Governments for rural and urban roads. These pavements represent more than 70 percent of the Australia's entire all weather road networks. Because of the great extent of the pavements in Australia were constructed with sprayed seal and thin asphalt surfacing, a realistic prediction of pavement performance of this group of pavements is a critical component of maintenance management of the road assets. It is essential that the performance be evaluated correctly by an

appropriate methodology. Using inappropriate methods can lead to incorrect prediction of pavement strength, which could result in higher maintenance and rehabilitation costs.

Back-analysis of the surface deflection bowl data can be used to estimate the elastic modulus of the subgrade from software packages such as EFROMD2 [1]. However, the errors and uncertainty associated with the back-analysis procedures generally limit their use to the development of indicative pavement models that explain past performance and hence can assist in the design of rehabilitation treatments [2]. In most cases it would be inappropriate to use back-analysis for determining a design CBR for new pavements or verifying the constructed subgrade support conditions with a sufficient degree of confidence. In part, this is because back-analysis does not provide unique modulus solutions and the values may differ from the measured values traditionally used for the design of new pavements.

It is also common for the back-analysis of a data file representing many test locations to return only a limited number of useable solutions, which then introduces a bias or uncertainty about the true characteristic value. Furthermore, it is usually difficult to accurately represent the actual variability of in situ subgrades by a theoretical model that requires defined sublayer thicknesses. The back-calculated modulus values are generally within a factor of 2 of the true value, and this may be unacceptable for many situations. The EFROMD2 user manual warns that even small average errors of 0.5% between measured and calculated deflections does not guarantee accurate predictions of moduli, critical stresses and strains [2].

In view of the concerns mentioned in the 2012 Austroads Guide [2], research work in the area of back-analysis is required to provide some answers to the effectiveness of the subgrade models in the back-calculation programs. The principal objective of this paper is to present the issues and problems pertaining to back-analysis of thin surfaced flexible pavements that possess highly nonlinear subgrade behavior. The back-calculation of the pavement structures is performed using software programs CIRCLY5 [3] and EFROMD2 [1]. The effectiveness of the built-in nonlinear model in EFROMD2 in modelling stress-dependent subgrade moduli will be discussed.

Modeling of Subgrade Nonlinearity

The nonlinear relationships that are known to exist between the modulus of a material and its stress state are addressed in different ways by linear elastic and by finite-element methods. With the layered linear elastic programs, the modulus of the layer is adjusted based upon the stress conditions in the layer beneath the load. Because the modulus varies with the stress state, it changes continuously from what it is beneath the load to its value at a remote distance from the load [4]. For the past twenty years, research has clearly demonstrated that, for the majority of fine-grained subgrade soils, resilient modulus decreases with increasing deviatoric stress levels, thus exhibiting stress-softening type behaviour [5]. Pavement materials behave differently when applied stresses are varied. Under a wheel load, the behaviour of bound materials such as asphalt concrete and cement treated materials can be considered as linear elastic, whereas granular base course materials and fine subgrade materials often display stress-dependent characteristics. Previous laboratory studies have shown that elastic of resilient response of granular materials in base, subbase and subgrade soils follow a nonlinear, stress dependent behaviour under repeated traffic loading [6, 7]. Unbound granular materials exhibit stress-hardening, whereas fine grained soils show stress-softening type behaviour.

The nonlinearity behaviour of the subgrade material is analysed by computing the Surface Modulus using Boussinesq's equations [8] as shown below. The maximum deflection (D_0) underneath the centre of the load was used to compute the subgrade Surface Modulus as shown in

Equation 1 and the deflection recorded at sensors D_{200} , D_{300} , D_{450} , D_{600} , D_{900} and D_{1500} were used for calculating the Surface Modulus as in Equation 2.

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

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

where, $E_0(0)$ is the subgrade surface modulus at the center of the load (MPa). $E_0(r)$ is the subgrade stiffness modulus at distance r (MPa). ν is the poisson ratio (0.35) and R is the radius of the plate. σ_0 is the constant pressure (kPa) and r is the distance from the center of the loading plate (mm). D_0 is the deflection underneath the centre of the loading plate (mm) and D_r is the deflection at distance r (mm).

The exponential n value is the material constant and is taken as a measurement of the nonlinearity of subgrade. If n is computed to be zero the material is said to be linear elastic. As n decreases toward a larger negative value between -0.1 and -1, the nonlinearity of the subgrade material becomes more and more pronounced. The equation to be used for computing n is as follows [9]:

$$n = \frac{\log\left(\frac{E_0(r_1)}{E_0(r_2)}\right)}{2 \times \log\left(\frac{r_2}{r_1}\right)} \quad (3)$$

where, n is material constant and $E_0(r_1)$ is the subgrade surface modulus at a distance r_1 (MPa). $E_0(r_2)$ is the subgrade stiffness modulus at distance r_2 (MPa). r_1 is the distance r_1 from the center of the loading plate (mm) and r_2 is the distance r_2 from the center of the loading plate (mm). $E_0(r)$ is the surface modulus at a distance r larger than the equivalent thickness of the pavement. In the equivalent layer theory of Odemark [10], overlaying (pavement construction) layers with different thicknesses and moduli are combined into one layer with an equivalent thickness.

Subgrade nonlinear behavior of thin surfaced flexible pavements can also be analyzed using Simplified Deflection Modeling (SDM) [11]. In the studies carried out by Chai & Kelly [12] and Chai et al. [13], it was found that FWD deflection data obtained from the Southeast Queensland's Long-Term Pavement Performance (SEQ-LTPP) sites can be modelled accurately using SDM. The exponential curve in SDM was found to have the desired characteristics that match the FWD deflection bowls. The parameters used in the model are explained as follows:

$$Y_r = K_1 e^{(-r/K_2)} \quad (4)$$

where Y_r is the FWD deflection at the respective sensor location (micron) and r is the respective sensor offset location (millimetres). K_1 is equal to deflection at D_0 in micron and K_2 is the structural parameter at the respective sensor location. For deflection at sensor D_{900} , the equation becomes:

$$Y_{900} = K_1 e^{(-900/K_{2,900})} \quad (5)$$

$$K_{2,900} = \frac{-900}{(\log e D_{900} - \log e D_0)} \quad (6)$$

where Y_{900} is the FWD deflection at the sensor location D_{900} (micron) and $K_{2,900}$ is the K parameter for FWD deflection at D_{900} . The rationale of using the D_{900} data is that the D_{900} deflection has been found to reflect a subgrade response that remains essentially unaffected by the structure of the overlying pavement [14]. Deflection D_{900} data is utilized because the deflection sufficiently far from the impact load is largely contributed by the subgrade. The D_{200} and D_{300} are not used because the deflections are indicative of the structural strength of the granular layers. D_{1500} deflection is not considered in the model because the dynamic effect of the FWD load on thin surfaced asphalt pavement, influences mainly the pavement materials near the impact load at the time of contact. Sensor D_{1500} positioned at 1.50 m away from the impact load is approximately four to six times the total thickness of the pavement layers and it would be outside the influence zone.

The parameter $K_{2,900}$ is found to have a direct relationship with the material constant, n value and the parameter can be used as a measurement of the degree of nonlinearity. The relationship between $K_{2,900}$ parameters and n values has been developed and the equation can be expressed as follows:

$$K_{2,900} = 435e^{(n/0.4546)} + 143 \quad (7)$$

where $K_{2,900}$ is the K parameter for FWD deflection at sensor location D_{900} (micron) and n is the degree of nonlinearity. When the degree of nonlinearity, n value is -0.50, $K_{2,900}$ for the particular deflection basin is computed to be 288. As the degree of nonlinearity increases to -1.00, $K_{2,900}$ decreases to 191. It can be observed that when $K_{2,900}$ is smaller than 300, the deflection basin is associated with high degree of subgrade nonlinearity. For moderate degree of nonlinearity, $K_{2,900}$ falls within the range of between 300 to 500. As $K_{2,900}$ increases and approaches 500, the pavement structure is observed to possess linear elastic behaviour with n value is nearly equal to zero. Using the newly developed relationship, the degree of subgrade nonlinearity can be defined using the $K_{2,900}$ and n value as shown in Table 1.

Table 1: Definition of Degree of Nonlinearity of Subgrade [11]

Degree of subgrade nonlinearity	$K_{2,900}$	n -value
Linear	>500	0.00
Moderate	300 to 500	0.00 to -0.50
High	<300	<-0.50

Stress Dependent Subgrade Models

At the early stage in the development of the back-analysis procedure, the accuracy of the nonlinear subgrade model was evaluated and the details have been described by Brown et al.[15]. In the study, the FWD was used to obtain deflection response on an experimental road. In-situ stresses and strains under the FWD loading were obtained from pressure cells and strain coils embedded at the top of the subgrade layer. Then, separate back-analysis techniques were undertaken assuming the subgrade layer to be either linear or nonlinear in behaviour. The study demonstrated that when subgrade nonlinearity was included, a distinct improvement in accuracy for the deflection bowl match was recorded. Moreover, correlation with the in-situ stress and strains gave a significant improvement over the linear model, with an accuracy of better than 10% underneath the load [16].

The subgrade characteristics have significant influence on the surface deflection and this layer has been modelled using a nonlinear, stress-strain relationship developed from extensive laboratory testing by Brown et al. [17]. The resultant stress-dependent elastic stiffness is as follows:

$$E_r = A \left(\frac{p'_0}{q_r} \right)^{B_2} \quad (8)$$

where E_r is the elastic stiffness of soil(MPa) and p'_0 is the mean normal effective stress due to self-weight of the pavement above the point concerned. q_r is the deviator stress due to wheel loading. A and B are soil constants.

Pavement materials behave differently when applied stresses are varied. Under a wheel load, the behaviour of bound materials such as asphalt concrete and cement treated materials can be considered as linear elastic, whereas granular base course materials and fine subgrade materials often display stress-dependent characteristics. Previous laboratory studies have shown that elastic of resilient response of granular materials in base, subbase and subgrade soils follow a nonlinear, stress dependent behaviour under repeated traffic loading [18, 19]. Unbound granular materials exhibit stress-hardening, whereas fine grained soils show stress-softening type behaviour. In general, a granular base course material has a higher modulus with increasing applied stress. The stress dependent modulu of granular material is expressed as [20]:

$$E_{gr} = E_1 \left(\frac{\sigma_m}{\sigma_{ref}} \right)^n \quad (9)$$

where,

- E_{gr} = stiffness modulus of granular material (kPa)
- E_1 = material parameter which can be dependent on stress ratios
- σ_m = $1/3(\sigma_1 + \sigma_2 + \sigma_3)$ is the mean principal stress (kPa)
- σ_{ref} = the reference stress of 100 kPa
- n = material constant

The modulus of a fine subgrade material decreases with increasing applied stress. The stress-dependent model for subgrade modulus can be expressed as [20]:

$$E_{sg} = E_{\max} \left(1 - \frac{\sigma}{\sigma_{ref}} \right)^p \quad (10)$$

where,

E_{sg} = stiffness modulus of subgrade material (kPa)

E_{\max} = material constant

σ = $(\sigma_1 - \sigma_3)$ is the deviator stress (kPa)

σ_{ref} = the reference stress of 300 kPa

p = material constant

Equations 9 and 10 are incorporated into EFROMD2 to simulate non-linear characteristics of granular layers and subgrade sub-layers having finite thicknesses respectively.

CIRCLY is an integral component of Austroads Pavement Design Guide [21] that is widely used in Australia and New Zealand. CIRCLY is an elastic layer analysis program that can provide forward calculation of the stresses, strains and deflections within the pavement system caused by a specified loading. The analytical solutions for the stresses, strains and displacements are found by integral transform methods [3]. The analytical solutions involve the integrals of the form as shown below:

$$I = \int_0^{\infty} A(k) J_{\eta}(k) J_{\tau}(kr) \exp(\pm \delta kz) k^{\mu} dk \quad (11)$$

Where J = Bessel function of the first kind and r, z = multiples of the loaded radius. The integrals are evaluated using Patterson's method. The same upper limit of integration is used for all the integrals associated with a given loaded radius and layered system, and is independent of the prescribed calculation points (r, z). This allows values of $A(k)$, $J_{\eta}(k)$ and $J_{\tau}(kr)$ to be stored, minimising unnecessary re-calculation [3].

Semi perpetual pavement structures that exhibit linear subgrade behaviour were back-analyzed using the CIRCLY and the study found that good convergence of the FWD deflection bowls have been achieved using the program [22]. The study shows that the FWD central deflections of the semi-perpetual pavements were reported to be between 230 to 240 microns and the deflection curvature is less than 100 microns. The horizontal tensile strain of the semi-perpetual structure varies from 102 to 187 micro-strains and the vertical compressive strain was analyzed to be between 65 to 98 micro-strains.

Methodology

FWD and DCP were conducted to assess the subgrade CBR of the thirty eight pavement test sections selected from the road network in South East Queensland. More than 200 FWD test points were carried out at the test sites. From pavement coring, the thickness of the asphalt layers was found to be between 40 to 50mm. The granular base layers vary from 160 to 200mm in thickness. For the pavements, FWD deflection basins were measured and reported at distances of 0, 200, 300, 450, 600, 900 and 1500 mm from the centre of the impulse test load. These deflections are denoted as D_0 , D_{200} , D_{300} , D_{450} , D_{600} , D_{900} and D_{1500} , respectively.

Three repeat ‘drops’ were conducted at each test point, with the data from the third ‘drop’ was used for reporting and analysis purposes. The measured deflections were then ‘normalised’ to the appropriate surface stress, to correspond with operating tyre pressures. Deflections from FWD testing were ‘normalised’ to the relevant target load by multiplying the measured deflections by the ratio of the target load to the actual load. With a standard 300 mm diameter loading plate, each target load corresponds to a specific surface stress, as shown in Table 2.

Table 2: Target FWD test loads and corresponding surface stresses [23]

Target test load	Corresponding surface stress	Rounded surface stress
35 kN	495 kPa	500 kPa
40 kN	499 kPa	550 kPa
50 kN	707 kPa	700 kPa

Dynamic Cone Penetrometer (DCP) is the direct field method used to estimate the subgrade CBR for cohesive soils in accordance with Australian Standard AS 1289.6.3.2 (1997) [23]. As the penetration cone is driven through the subgrade layer of pavement, for each drop of the standard weight and the penetration is measured in mm/blow. Austroads [2] presented the correlation between CBR value and DCP test for fine-grained cohesive soils as shown in Fig.3 and the relationship can be expressed as:

$$\log_{10} CBR = 2.154 - 1.555 \log_{10} DCP \quad (12)$$

where CBR is the subgrade California Bearing Ratio (%) and DCP is the dynamic cone penetrometer (mm/blow).

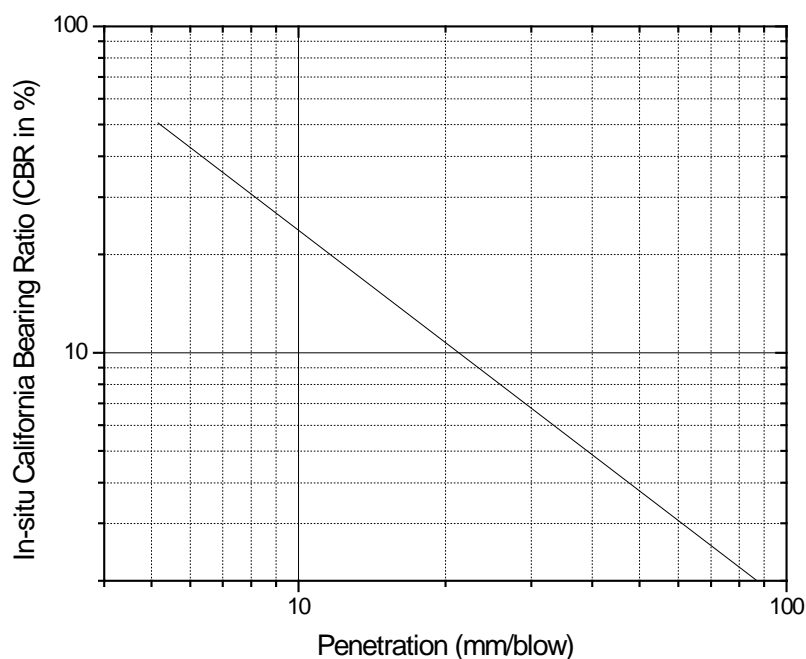


Figure 1. Correlation between DCP and subgrade CBR [2]

The AASHTO (1993) design guide [24] suggests that the resilient modulus of fine-grained soils can be estimated as follows[25]:

$$M_r \text{ (psi)} = 1,500 \text{ CBR} \quad (13)$$

Where M_r = subgrade Resilient Modulus (psi) and CBR_{subgrade} = subgrade CBR (%).

A comparison of subgrade CBR backcalculated using CIRCLY5 and EFROMD2 programs and the in-situ CBR values derived from DCP was then carried out. The backcalculated CBR was converted to resilient modulus using Eq. 13.

Backanalysis and results

FWD data from thirty-eight pavement test sections were analysed using CIRCLY5 and EFROMD2. The comparison between the DCP derived stiffness modulus and the back-calculated stiffness modulus for all the thirty-eight are depicted in Figures 2 to 3 and the results of eleven selected test sections are presented in Tables 3 and 4. The D_0 deflection varies from 642 micron (0.642 mm) to 2,451 microns (2.451 mm). Relatively small deflections were recorded at the D_{900} sensors. At this sensor location, the deflection varies from 3 (0.003 mm) to 59 microns (0.059 mm) and is nearly identical despite the increase in the deflection in D_0 . These are particularly obvious for Test Sites No.10 and 11. One reason for these consistently small deflections is the dynamic affect of the FWD load which influences mainly the pavement materials near the impact load at the time of contact. The degree of subgrade nonlinearity (K_{900}) was computed using Eq. 6 and the values were included in Table 3. It can be observed that majority of the $K_{2,900}$ parameters are less than 300 and the deflection bowls are said to possess high degree of nonlinearity. Three of the test sections show moderate degree of nonlinearity with K_{900} ranges from 316 to 343.

The results of the back-analysis show that CIRCLY5 over predicted the stiffness modulus values by a sizable margin of errors. The forward calculation program over predicts the in-situ stiffness modulus by a factor of between 2 and 50 respectively. To achieve convergence of the deflection bowls, very high stiffness modulus have been assigned for subgrade and very low stiffness was set for the road base layer. The nonlinearity effects are problems encountered in back-calculation analyses of these groups of pavements and it can yield back-calculated results with superficially high subgrade stiffness modulus and extremely low stiffness modulus at the road base layer. The nonlinearity is identified by a greater apparent subgrade modulus at the outer sensor location than the expected value at that point or the modulus directly underneath the loading plate. If the subgrade is modelled as linear elastic material, then the greater modulus value is calculated and assumed to be constant throughout. When the modulus for the layer on top of the subgrade is being calculated, the overestimated subgrade modulus is compensated for by assigning a lower modulus for the layer on top of the subgrade in order to match the deflection measured at that point. This condition is often described as “inverted pavement” where the subgrade stiffness modulus is much greater than the road base stiffness modulus. This phenomenon can result in errors and incorrect modelling of the pavement responses.

Table 3: Falling Weight Deflectometer data with Degree of Nonlinearity

Section	T1 (mm)	T2 (mm)	Sub-grade (MPa)	FWD deflection bowls (micron)							K_{900}
				0	200	300	450	600	900	1500	
1	40	165	160	642	472	291	155	79	21	8	263
2	40	185	105	1,214	911	692	361	210	59	22	297

3	40	170	125	1,044	719	515	264	70	20	17	227
4	40	170	110	655	450	326	200	123	44	12	333
5	45	275	150	653	464	322	179	97	38	23	316
6	40	260	130	743	573	403	233	136	54	25	343
7	50	200	30	2,309	1,763	1,257	698	344	42	21	224
8	40	140	60	2,451	1,823	1,257	668	281	27	2	199
9	40	155	170	680	518	352	194	99	19	6	251
10	40	205	140	757	519	282	72	7	4	1	171
11	50	190	90	1,623	1,219	836	429	153	3	1	143

Note: T1=Asphalt thickness, T2=Roadbase thickness, Data in fourth column = in-situ Subgrade stiffness modulus

Table 4: Back-analysis results from CIRCLY5 and EFROMD2

Section	EFROMD2		Sub-layering of Subgrade			Error (%)	CIRCLY5			
	Asphalt (MPa)	Roadbase (MPa)	Layer -1 (MPa)	Layer-2 (MPa)	Layer-3 (MPa)		Asphalt (MPa)	Road-base (MPa)	Subgrade (MPa)	Error (%)
	E1	E2	E _{sg1}	E _{sg2}	E _{sg3}		E ₁	E ₂	E _{sg}	
1	10,000	222	57	50	300	64	5,000	100	750	>100
2	10,000	150	10	69	260	90	3,500	50	250	>100
3	3,563	269	25	13	300	80	3,000	150	750	>100
4	10,000	496	35	50	278	68	5,000	150	300	>100
5	5,524	213	31	68	300	79	2,000	150	400	>100
6	8,927	192	29	47	276	77	2,000	150	250	92
7	3,743	150	10	13	283	66	1,500	30	400	>100
8	666	150	13	10	300	80	800	30	750	>100
9	10,000	417	82	36	300	52	2,500	150	900	>100
10	10,000	150	68	300	300	51	880	120	4,500	>100
11	5,163	150	11	24	300	87	800	50	4,500	>100

Note: Subgrade sub-layering, Layer 1=Layer 2=Layer 3=200mm, error (%) = percentage error in predicting subgrade stiffness modulus

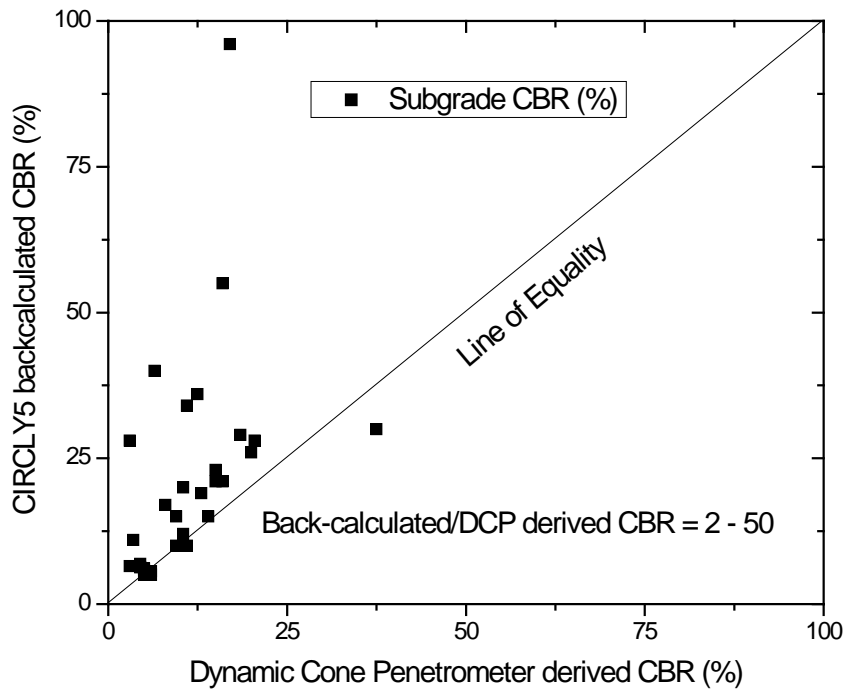


Figure 2. CIRCLY5 backcalculated CBR versus DCP derived subgrade CBR

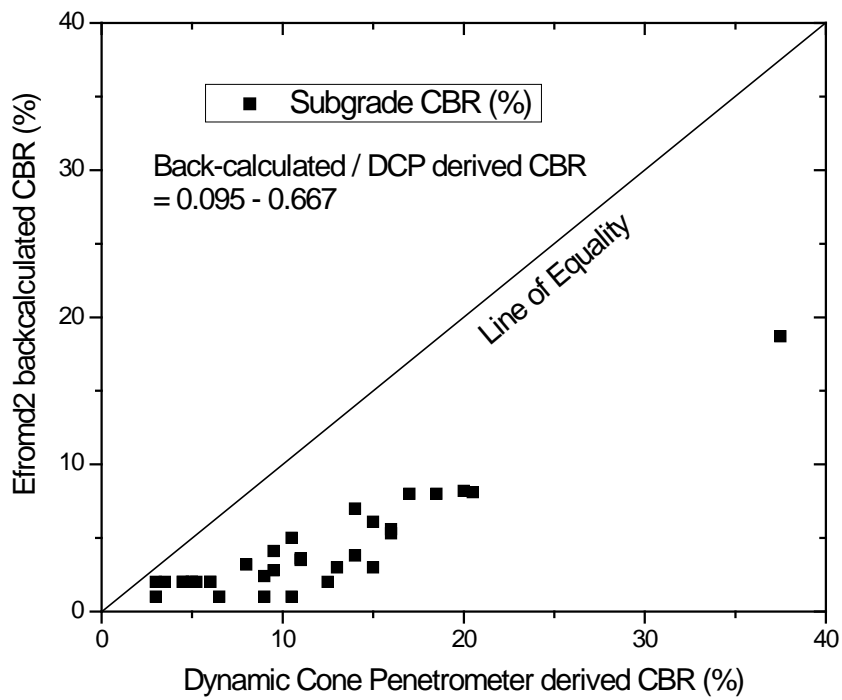


Figure 3. EFROMD2 backcalculated CBR versus DCP derived subgrade CBR

On other hand, EFROMD2 program consistently over predicts the asphalt stiffness and under predict the subgrade stiffness modulus for the highly nonlinear pavements. Large errors in predicting the subgrade stiffness modulus were observed as the degree of non-linearity increases and on an average an error of more than 60% was reported. It is observed that EFROMD2 under predicted the in-situ CBR by a factor of between 0.095 and 0.667 despite the sublayering of the subgrade was introduced. The error checks indicate convergences are not within the acceptable levels of tolerance for the back-calculation program. Although the pavement structural analysis program EFROMD2, take into account the stress-dependent moduli, the built-in nonlinear subgrade models (see Eq. 10) in this computer program appear to be not effective in modelling sprayed seal and thin asphalt pavement structures which exhibit high degree of nonlinearity.

Conclusions and recommendations

The issues pertaining to the back-calculation of flexible pavements that possess highly nonlinear subgrade behaviour have been presented. A simple approach to compute the degree of subgrade nonlinearity has been introduced. The findings from the study are summarised as follows:

- The study shows that relatively small deflections were recorded at the D_{900} sensors. This is due to the dynamic affect of the FWD load which influences mainly the pavement materials near the impact load at the time of contact;
- It can be observed that majority of the $K_{2,900}$ parameters are less than 300 and the deflection bowls are said to possess high degree of nonlinearity. Three of the test sections show moderate degree of nonlinearity with K_{900} ranges from 316 to 343;
- The results of the backanalysis show that CIRCLY5 over predicted the CBR values by a sizable margin of errors. The forward calculation program over predicts the in-situ CBR by a factor of between 2 and 50 respectively for highly nonlinear pavements;
- Previous study [22] found that good convergence of the FWD deflection bowls has been achieved using CIRCLY5 program for back-analyzing pavement structures that exhibit linear subgrade behaviour;
- EFROMD2 program consistently over predicts the asphalt stiffness and under predict the subgrade stiffness modulus for the highly nonlinear pavements. Large errors in predicting the subgrade stiffness modulus were observed as the degree of nonlinearity increases, and on an average an error of more than 60% was reported; and
- The built-in nonlinear subgrade models in EFROMD2 program appear to be not effective in modelling sprayed seal and thin asphalt pavement structures which exhibit high degree of nonlinearity.

The above study highlighted a need to develop a more robust pavement non-linear subgrade model for modelling highly nonlinear pavement behaviours. It is also recommended that detailed assessment of the degree of subgrade nonlinearity be carried out prior to backcalculation. The aim is to achieve a more realistic prediction of pavement responses in back-analysis of thin surfaced flexible pavements that possess nonlinear subgrade materials.

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