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PFWD, DCP and CBR correlations for evaluation of lateritic subgrades

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The evaluation of subgrade strength plays a major role in pavement design. An understanding of subgrade properties enables the selection of road materials for sub-base and base courses. In developing countries like India, apart from the use of well-established traditional pavement evaluation techniques such as the California bearing ratio (CBR) test and the dynamic cone penetrometer (DCP) test, the use of non-destructive testing devices such as the portable falling weight deflectometers (PFWDs) has gained popularity in recent years. This is mainly because of the inherent capability of PFWDs in obtaining quick estimates of the modulus of subgrade in addition to their simplicity in design and portability. Thus, there exists a need to correlate the results obtained using PFWDs with those obtained using traditional approaches such as the CBR and the DCP for the benefit of road engineers. This work focuses on exploring the correlations between these approaches for lateritic soils in Dakshina Kannada district, India.

Keywords: DCP; PFWD; CBR; correlation; modulus; lateritic subgrade

1. Introduction and problem definition

Subgrades provide structural stability to pavements by transmitting superimposed traffic loads safely to the soil strata below. The evaluation of subgrade strength plays a major role in the design of pavements since traffic loads need to be transmitted in a manner in which the subgrade deformation is within elastic limits and the shear forces developed are within safe limits under adverse climatic and loading conditions. In this connection, subgrades need to be evaluated for the soil stiffness and strength. In addition to this, an investigation into the influence of the soil properties of the subgrade on pavement performance is also essential.

In a number of circumstances, road engineers come across situations where subgrades need to be strengthened in order to improve their load-carrying characteristics. Also, road engineers adopt alternative construction practices and new road-construction materials including the use of recycled aggregates in an effort to economise on road construction costs (Fleming *et al.* 1998). Thus, regular evaluation of the effectiveness of the improved subgrades needs to be performed.

Traditionally, flexible pavements are designed based on the California bearing ratio (CBR) approach or by considering elastic deformations as in the case of Burmister (1958) layer theory. The CBR method of analysis gives more importance to the estimation of the strength of the subgrades and the pavement layers, while the analysis based on quality control of pavements relies more on the determination of *in situ* density and moisture content. But according to Chen *et al.* (1999) and Livneh and Goldberg (2001), although 'density' is a good indicator of the strength of granular subgrades, it is also necessary to investigate the modulus of the subgrade, since these measures represent different natural characteristics.

The portable falling weight deflectometer (PFWD) is a non-destructive testing device that assists in rapid estimation of the elastic modulus of subgrades. The use of non-destructive approaches to pavement evaluation incorporating the use of PFWDs has gained popularity in recent years due to their inherent capability in obtaining quick estimates of the modulus of the subgrade in addition to their simplicity of design. In view of this new development, there exists a need to correlate the results obtained using PFWDs with those obtained using traditional approaches such as the dynamic cone penetrometer (DCP) and the CBR for the benefit of road engineers.

Moreover, with the stress on improving the transport infrastructure of the country to achieve higher growth rates, and with the fast pace of industrialisation taking place in the District of Dakshina Kannada of coastal Karnataka in peninsular India, the existing road infrastructure is being expanded to a large extent. The existing two-lane roads are being broadened to accommodate four- and six-lane traffic. But approximately 40% of the subgrades available in the District of Dakshina Kannada comprise of soils of laterite origin.

This work focuses on exploring the correlations between these approaches for lateritic soils of Dakshina Kannada district, India. A number of correlations have been developed between the modulus of subgrades to DCP

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observations and the CBR values, but investigations on lateritic soils are limited. Thus, the first objective of this study was to develop correlations between the CBR and the DCP observations. The second objective is to examine the relationships between the modulus of the subgrades and the DCP values. This work also provides a discussion on the effect of geotechnical parameters on the prediction of the CBR and the modulus of subgrades for lateritic soils of the Dakshina Kannada district of India.

1.1 *Need for correlating DCP studies and CBR investigations*

In the field of subgrade evaluation, the CBR method was adopted by numerous states, counties and federal agencies of the USA, and also by various international agencies. Later, the use of the DCP test became popular and the DCP test was used mainly for estimating the *in situ* CBR values of subgrades indirectly (WSDoT web site).

The DCP is considered to be a device that can be easily fabricated. It serves as an excellent tool for inspection and evaluation of especially hard soil layers. This device has the capability to assess the level of compaction and its uniformity (Burnham 1996, Siekmeir *et al.* 1999). The advantages of the DCP include low investment costs, portability and capability for rapid testing and evaluation of subgrades and pavement layers. DCP tests can be conducted within 15 min in order to make reliable estimates of the CBR values of underlying layers effectively (Jahren *et al.* 1999). Due to this reason, the DCP test for subgrade evaluation has gained popularity. Though a number of studies have been performed for correlating DCP observations and CBR readings, sufficient investigations have not been conducted on lateritic subgrades of India.

1.2 *Need for correlating DCP observations and subgrade moduli*

In the field of pavement evaluation, road-construction authorities rely mainly on information on the stiffness of pavement layers and on the modulus of subgrades as references along with supplementary data on density and moisture content. Many times, it becomes necessary to estimate the subgrade stiffness or modulus of the pavements before and after their construction as part of the quality-control measures and also for quality assurance (Chen *et al.* 2005). The traditional approach towards determination of the modulus of subgrade using the plate-load test is time consuming, labour intensive and cumbersome. However, developments in the field of instrumentation have led to the invention of a number of non-destructive testing devices that are more efficient in data collection.

Currently, falling weight deflectometers (FWD), GeoGauges, dirt-seismic pavement analysers (DSPA) and laboratory-based repetitive triaxial tests are used to estimate the modulus of elasticity of pavement layers (Livneh and Goldberg 2001, Nazarian *et al.* 2002, Rahim and George 2002, Sawangsuriya *et al.* 2002). But each of these devices has its own advantages and disadvantages. The use of FWDs requires the deployment of trained personnel in addition to heavy investments although the results are reliable, while the use of laboratory-based repetitive triaxial tests is not generally adopted due to cumbersome procedures in addition to the need for skilled professionals (Chen *et al.* 2001, Rahim and George 2002). In comparison to the above, analysis using DSPA is quick and easy, but the modulus value determined is considered to vary over wide ranges. The results obtained using GeoGauges show more consistency, but are highly sensitive to the preparation of the surface to be analysed (Chen *et al.* 2005).

However, the invention of the PFWD has revolutionised the field of pavement evaluation mainly due to its simplicity, ease of use, portability, reliability and ruggedness. But this device too provides only a composite stiffness of all layers up to an influence depth of 266.7–279.4 mm (Abu-Farsakh *et al.* 2004). The PFWD is now considered as a light weight deflectometer (LWD), and the test standards for the same are being finalised by ASTM (ASTM 2008).

2. Literature survey

Considering the importance of evaluation of the stiffness of subgrades in pavement design, the present investigations concentrate on the study of correlations between observations made using the PFWD, the DCP and the CBR on laterite soils for field conditions. This section provides a brief review of literature on correlation studies for the above investigations.

2.1 *Correlations between DCP and unsoaked CBR observations*

Van Vuuren (1969), Kleyn (1975) and Harison (1983) have reported the results of preliminary studies on pavement evaluation using the DCP. Livneh (1989) performed a number of studies on exploring the correlations between the observed values for the DCP and the CBR and developed 20 relationships (Luo *et al.* 1998).

Investigations by Smith and Pratt (1983), Harison (1987), Chua (1988), Livneh and Ishai (1988), Livneh *et al.* (1992), Ese *et al.* (1994), Livneh and Livneh (1994) and Coonse (1999) have proved the reliability of the DCP in estimating the soil stiffness and its capability in estimating the CBR values more accurately.

Investigations conducted at the Waterways Experiment Station (WES) focused on soils with CBR values less than 10% and fat clay soils. Webster *et al.* (1992) have also reported a relationship between the CBR value and the penetration rate (DCPI) expressed in millimetre per blow, developed earlier by the US Army Corps of Engineers for a wide range of granular and cohesive materials. This relationship has been adopted by many researchers (Livneh 1989, Webster *et al.* 1992, Siekmeir *et al.* 1999).

Gabr *et al.* (2000) investigated the use of DCP for evaluation of pavement distress for experiments conducted on subgrades overlaid with aggregate base course of granite of Los Angeles value of 20% and developed the expression shown in Equation (1).

$$\log(\mathrm{CBR}) = 1.4 - 0.55\log(\mathrm{DCPI}). \tag{1}$$

Most of the above investigations dealt with correlations between the CBR values and the DCPI observations for granular and cohesive soils, while studies using the DCP were made on aggregate base courses of pavements.

2.2 *Correlations connecting subgrade modulus to DCP and CBR observations*

This section provides details on a review of literature related to the development of correlations between observations of the subgrade modulus and the CBR and the DCP readings. Powell *et al.* (1984) proposed the most widely accepted relationship between the CBR value and the modulus of the subgrade (E_s) measured in MPa.

Chua and Lytton (1981) developed a theoretical relationship between the DCPI and the elastic modulus (E_s) using an additive constant that depended upon the principal stress difference as reported by Abu-Farsakh *et al.* (2004). Seyman (2003) has reported the use of relationships developed by Pen (1990) where the back-calculated layer moduli (E_s) of pavements can be estimated using the penetration rate (DCPI) of DCP tests where the calculation of the layer moduli was performed using the Phoenix system and the Peach system, respectively.

De Beer (1990) proposed a simple correlation between the back-calculated elastic modulus (E_s) determined using a heavy vehicle simulator and the penetration index (DCPI) expressed in mm per blow. Chen *et al.* (2005) have reported studies conducted by AASHTO (1993) for the design of pavements where a correlation model was developed for the determination of the modulus of elasticity (E_s) based on CBR observations for experiments conducted on fine-grained soils with a soaked CBR of 10 or less. This equation provides a rough estimate of the moduli since the relationship was developed based on moduli values ranging from 750 to 3000 times the CBR value.

Nazzal *et al.* (2007) have reported a relationship developed by Chen *et al.* (1999), connecting the back-calculated resilient modulus (M_{FWD}) measured using the FWD, and the DCPI. A relationship developed by Konrad and Lachance (2000) relating the penetration index (DCPI) for a large DCP with a 51 mm diameter cone, and the elastic modulus back-calculated from plate-load tests (E_{PLT}) measured in MPa for unbound aggregates, and natural granular soils, has been reported by Abu-Farsakh *et al.* (2004).

Chen *et al.* (2005) combined the results of the studies of AASHTO (1993) and Powell *et al.* (1984) to obtain a direct relationship between the penetration rate (DCPI) for DCP tests measured in mm per blow and the layer moduli (calculated in MPa). Further studies by Chen *et al.* (2005) using DCPs and FWDs for roads in Texas provided correlations connecting the layer moduli (E_s) and the penetration rate (DCPI) measured in mm per blow for DCP tests, as expressed in Equation (2). This relationship had an R^2 value of 0.855 and a mean-square error of 0.15.

$$E_s = 537.76 \times \mathrm{DCPI}^{-0.6645}. \tag{2}$$

Fleming *et al.* (2000) conducted field tests correlating the observations of the moduli of subgrades obtained using the FWD and the results obtained using the light falling weight deflectometers (LFWD) and PFWD such as the Prima 100 LFWD (LFWD-Prima100), the German dynamic plate (GDP) and the Transport Research Laboratory (prototype) foundation tester (TFT). The studies showed that the modulus of the subgrade (M_{FWD}) measured using the FWD was closely correlated with the values estimated by Prima 100 LFWD ($E_{\mathrm{lfwd\text{-}Prima100}}$). However, the values estimated using the GDP (E_{GDP}) and the TFT (E_{TFT}) were comparatively less consistent.

Nazzal (2003) also conducted studies on correlating back-calculated resilient moduli values (M_{FWD}) obtained using FWDs and the estimated values of the modulus of subgrade (E_{lfwd}) obtained from observations using LFWDs. A nonlinear multiple regression analysis was conducted by Nazzal *et al.* (2007) relating the modulus measured using the FWD (M_{FWD}) to that measured using the LFWD (E_{LFWD}).

The investigations conducted above indicate that FWDs and LFWDs or PFWDs are capable of providing better estimates of the modulus of subgrades. Based on this premise, it was felt that further investigations could be performed to explore correlations between the subgrade moduli values estimated using the PFWDs and the DCP and CBR readings. This would be of special advantage to road engineers of developing nations and lesser developed countries that mainly rely on the use of CBR values for pavement design.

3. The study area

Investigations related to the present work were performed in the Dakshina Kannada district of the State of Karnataka, India. Dakshina Kannada is a narrow strip of land extending in the north–south direction along the west coast of India between 12°27′ and 13°58′N, half-way between Mumbai and Kanyakumari. Along the east–west direction, it extends from the Western Ghats to the Arabian Sea, between 74°34′ and 74°40′E. The soil of this region is predominantly lateritic in nature and also includes shedi soil, coastal alluvium and saline soils. The region has a humid tropical climate with an annual rainfall of about 4000 mm. The soil samples of subgrades were obtained from road-construction sites close to National Highway (NH) 17.

Lateritic soils are found in regions of high rainfall, high temperature and high humidity with alternate wet and dry periods that are conducive to laterisation. Laterite is a pedogenic and highly weathered natural material formed by the concentration of hydrated oxides of iron and aluminium, further oxidised to form insoluble precipitate of fine particles, occurring in various parts of India, especially in the Deccan Peninsula. They consist predominantly of mineral assemblages of goethite, haematite, aluminium hydroxide, kaolinite minerals and quartz. Further, concentration, dehydration and subsequent cementation of laterite form hard concretionary nodules. Sometimes, the particles coalesce into hard vesicular masses of honeycombed structure with cavities containing the host soil. Laterite formations in general consist of a top-hardened vesicular layer followed by a lithomargic clay (shedi) layer over the weathered residual soil and parent rock (Yaji and Gowda 1995). In Dakshina Kannada district, nearly 40% of the soils are lateritic in nature. These lateritic soils generally comprise silty sand (denoted by SM) and clayey sand (denoted by SC). The shear strength measured in terms of the cohesion and the angle of friction for the soil investigated in this study was found to vary between 0.1 and 17.57 kN/m^2 and 8° and 41°, respectively.

4. Description of the equipment

The following subsections provide details on the important equipment used in this study and their working principles.

4.1 *Working of the DCP*

The DCP, also known as the Scala penetrometer, was developed in 1956 in South Africa as an *in situ* pavement evaluation technique for evaluating pavement layer strength (Scala 1956). The DCP consists of a steel rod with a steel penetration cone of 60° cone angle and 20 mm diameter attached at one end. This can be driven into the pavement structure or subgrade using a sliding hammer of 8 kg weight falling through a height of 575 mm. The penetration of the cone can be measured up to a depth of 800 mm using a calibrated scale. However, it is also possible to measure penetrations of up to 1200 mm depth when fitted with an extension rod.

It may be noted that the diameter of the cone is slightly larger than that of the rod. This is to ensure that the resistance to penetration offered by the soil is exerted fully on the cone. The subgrade strength is measured in terms of penetration in millimetres per hammer blow. The DCP came to be increasingly used in many parts of the world for the evaluation of subgrades, granular material and lightly stabilised soils. A number of studies have been performed to correlate the results of the DCP test for the estimation of *in situ* CBR.

4.2 *Working of PFWDs*

Investigations on the use of more efficient devices for conducting pavement evaluation led to the development of LFWDs and PFWDs. These lightweight *in situ* testing devices were initially developed in Germany as an alternative to the plate-load test. These are now used extensively in Europe and Japan (Nazzal 2003). The LFWDs and PFWDs developed include the GDP, the TFT and the Prima 100 LFWD in Europe, the Middle East, Japan and the USA (Nazzal 2003). Cheaper and more efficient PFWDs such as the Loadman (Gros 1993), Inspector-2 (see Figure 1) and Zorn ZFG 2000 were also developed as part of this endeavour.

As in the FWD, a falling weight of a PFWD produces a predefined load impulse when it falls on a loading plate. The deflection measured using a geophone or an accelerometer located in the centre of the plate is used in estimating the elastic modulus based on a Boussinesq elastic half-space. In this concept, the assumption is that the soil subgrade extends for an infinite length along the horizontal direction, while the depth over which the load acts vertically is finite. The subgrade material is assumed to have a uniform Poisson's ratio.

The expression derived by Egorov (1965) as given in Equation (3) is used by the embedded software in the PFWD for calculating the modulus of the subgrade (E_{pfwd}). This expression was developed for determining the surface modulus of layered media. Generally, a Poisson's ratio (n) of 0.35 is assumed for the computation. In Equation (3), d_c represents the centre deflection of the loading plate of radius R, s represents the applied stress

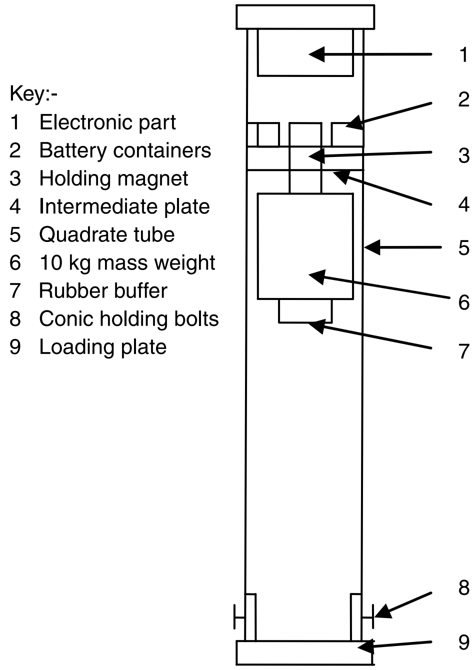

Figure 1. Inspector-2 PFWD.

and f represents a shape-cum-rigidity factor generally assumed to be equal to 2.

$$E_{\mathrm{pfwd}} = [f(1-n^2)s \times R]/d_{\mathrm{c}}. \tag{3}$$

One of the major advantages of PFWDs is that they are relatively cheap. They can also be easily transported, and it is easy and quicker to obtain measurements. Also, PFWDs and FWDs do not use radioactive material as is used in nuclear density gauges.

The PFWD is a light, portable device designed for determining the elastic modulus and other compaction parameters including the estimation of the bearing capacity of bound and unbound construction layers including subgrades, base courses and layers of pavements. It can also be effectively deployed in the estimation of the degree of compaction of embankments. This portable equipment is designed in a compact manner and is easy to handle in situations where space restrictions hamper the use of other devices. Various types of PFWDs have been developed, tested and used in Europe and other countries.

5. Details of the PFWD, DCP and CBR tests performed

The data on PFWD, CBR and DCP investigations for this study were obtained from 45 test sites along NH 17 between New Mangalore Port Trust and Mulky of Dakshina Kannada district, India. Among these 45 sites, 75% of the data was used for development of correlations, while 25% of the data was used for validation of the equations developed from this study.

PFWD observations were made on natural soil subgrade after removing the top 150 mm of loose topsoil. The readings were taken randomly for 12 points in test pits of 1000 mm square size, leaving a margin of 150 mm from the edge. The readings for the second blows were taken for each observation point, considering the first blow as the seating load, and the average values (E_{pfwd}) were reported. The readings for the second blows were always found to be about 15–20% more than that of the first blow. This was consistent with the observations made by other researchers (Steinert *et al.* 2005) who have reported a variation of 10% between the readings of the first drop and the second drop, and a variation of 1% between the readings of the second drop and the third to fifth drops. Steinert *et al.* (2005) also suggest that the first drop may be considered as a seating load, and that the reading may be neglected.

The Inspector-2 PFWD used in this study (Figure 1), developed and marketed by Englo of Estonia, weighs 16 kg and has a falling weight of 10 kg, with an impact duration varying between 5 and 15 ms. It is equipped with holding magnets that hold the falling weight at a specified height of 800 mm. This PFWD uses accelerometers to measure the readings as is the case with most PFWDs (Abu-Farsakh *et al.* 2004). The Young modulus is automatically determined by the embedded software, and the same is displayed on the LCD screen immediately after each test. The display also provides information on the deflection, the rebound deflection and the impulse duration. The manufacturer of the equipment has provided two base plates, one of 140 mm diameter and the other of 200 mm diameter, each of 5 mm thickness. The base plate of 140 mm was recommended by the manufacturer for Young's modulus values ranging from 0 to 1200 MPa, while the larger base plate was recommended for use in softer soils where the deflections were more than 5 mm, or when the estimated Young's modulus was lesser than 10 MPa (Englo 2005).

A layer of fine sand of up to 5 mm thickness was applied wherever the ground was found to be uneven or rough, so as to ensure proper contact between the loading plate of the deflectometer and the ground. Precaution was taken to see that the deflectometer was placed as vertically as possible within a tolerable error of 2–3° to the vertical.

DCP tests were then conducted at these locations immediately after the PFWD tests were completed. This approach was adopted since vibrations induced by the PFWD do not cause much disturbance to subgrade soils in a manner affecting the performance of the DCP. While performing the DCP test, the penetration cone of the DCP was first subjected to a seating load of one blow before commencement of the experiment. The number of blows required for a penetration of 300 mm after application of the seating load was then noted, and the rate of penetration per blow was found. The experiment was repeated for three different points for each pit and the average rate of penetration was found.

For the determination of the field moisture content, the field density and the unsoaked field CBR values, core samples were collected from each of the above locations and tested. The field density and the field moisture content were first determined according to Indian Standard specifications vide, IS: 2720-Part 29 (1966) and IS: 2720-Part 2 (1973a,b), respectively. The CBR tests were then conducted in the laboratory by simulating the field conditions. For a given volume of the standard CBR mould of 150 mm diameter and 125 mm height, the weight of soil required to fill the mould for the field density determined is calculated. The CBR mould was filled by compacting soil in three equal layers. A mild steel hammer of approximately 5 kg weight was used to compact each layer of soil to the required thickness. Three tests were performed for the soil obtained from each site, and the average of the three was reported as the CBR value. The CBR tests were performed according to Indian Standard specifications IS: 2720-Part 16 (1979). This alternative approach to find the unsoaked field CBR values was adopted due to lack of availability of equipment for conducting *in situ* CBR tests.

6. Results and discussions

Tables 1 and 2 provide details of the observations for investigations conducted using the PFWD, the DCP and the CBR for various locations. The field moisture content, the maximum dry density, the SD for E_{pfwd}, the DCPI and CBR values, the plasticity indices, the liquid limit and the percentage passing 75 μm sieve are also provided. The results obtained were analysed and the correlations were explored using Statistical Package for Social Sciences (SPSS).

6.1 *Correlation between CBR and DCP observations*

Eleven families of curves were tested using SPSS for the given data for exploring the correlations between the CBR

Table 1. PFWD, DCP and CBR observations comprising 75% of field data for the development of correlations.

Site #	E_{pfwd} (Mpa)	S_{pfwd}[a]	DCPI (mm/blow)	S_{DCPI}[a]	CBR (%)	S_{CBR}[a]	PI (%)	γ_d (kN/m^3)	W (%)	w_L (%)	p_{200} (%)
1	36.67	2.47	15.20	2.05	6.56	1.44	13.7	10.10	18.10	28.4	30.8
2	35.13	2.01	16.20	1.70	4.37	1.39	13.3	11.10	17.92	34.5	34.4
3	29.50	2.30	17.00	1.88	3.93	1.28	13.3	13.89	18.80	35.2	35.8
4	23.87	1.97	17.65	2.03	3.90	1.64	24.6	8.92	14.42	31.3	20.4
5	23.88	2.88	18.30	2.07	4.10	1.17	22.1	10.20	13.56	30.2	19.2
6	148.80	2.80	1.10	0.48	39.00	1.65	4.5	20.95	8.82	14.2	11.2
7	174.10	2.10	1.20	0.38	50.00	1.20	3.7	22.68	5.80	12.5	9.8
8	64.00	2.00	5.92	2.04	15.00	1.50	17.5	18.56	13.12	38.2	26.4
9	52.00	3.00	5.45	1.56	11.69	1.80	17.8	18.13	14.20	42.0	28.8
10	94.40	2.40	3.88	1.96	23.40	0.92	18.1	17.47	12.21	26.3	21.2
11	94.88	2.88	3.32	1.56	22.81	1.75	18.3	17.35	12.42	24.5	22.5
12	89.80	2.80	4.09	1.77	23.97	1.10	18.0	17.59	11.97	26.4	25.3
13	119.00	2.00	1.00	0.50	31.14	1.28	7.5	17.85	17.62	13.5	13.5
14	68.25	2.25	4.32	1.76	17.00	1.23	18.8	15.81	18.26	32.1	26.6
15	82.25	2.25	4.60	1.58	18.00	1.05	8.6	16.55	14.20	28.6	22.4
16	40.62	2.79	4.12	1.20	9.65	1.33	31.2	14.81	16.10	42.3	32.5
17	71.87	2.87	3.81	1.76	18.42	1.83	11.1	16.20	16.08	23.1	13.5
18	63.00	2.00	4.12	1.56	17.10	1.84	11.3	17.43	17.04	25.3	15.4
19	32.87	2.87	6.80	1.82	7.45	1.36	14.9	13.62	18.91	45.3	32.5
20	60.25	2.25	7.24	1.62	12.00	1.15	12.4	16.09	17.45	40.5	29.2
21	43.12	2.12	5.99	1.87	7.89	1.54	14.6	13.90	18.72	44.2	31.6
22	63.38	3.38	4.10	1.15	15.57	1.12	17.1	15.65	18.20	40.6	14.8
23	59.38	2.38	6.28	1.46	16.08	1.1	16.9	15.36	17.85	38.6	15.5
24	75.25	2.25	4.29	1.34	14.48	1.19	14.7	15.30	15.02	39.5	13.2
25	80.75	2.75	4.23	1.64	16.80	1.11	14.5	15.98	14.51	38.4	12.6
26	56.00	2.00	5.45	1.77	13.00	1.02	16.2	15.50	15.50	52.4	42.2
27	48.00	2.00	5.10	1.25	10.00	1.05	17.2	15.34	16.00	57.2	47.3
28	20.00	2.00	7.75	1.22	6.14	1.08	30.4	14.09	18.56	44.6	25.2
29	29.75	2.75	9.74	1.48	6.43	1.14	15.1	16.54	18.48	43.0	22.4
30	21.62	2.62	10.80	1.68	7.45	1.44	15.0	16.83	17.67	41.5	29.5
31	24.63	2.63	15.26	1.41	7.45	1.13	15.4	8.23	12.35	39.4	27.9
32	24.25	2.25	10.06	1.50	6.00	1.15	16.0	15.73	13.83	41.5	29.1
33	54.37	2.37	13.93	1.92	12.00	1.02	15.7	9.12	17.00	31.8	16.2
34	44.75	2.75	10.33	1.68	7.89	1.36	16.4	15.85	19.00	36.8	18.9

[a] S_{pfwd}, SD of E_{pfwd} values; S_{DCPI}, SD of DCPI values; S_{CBR}, SD of CBR values.

Table 2. PFWD, DCP and CBR observations comprising 25% of field data for the validation of correlations developed.

Site #	E_{pfwd} (Mpa)	S_{pfwd}[a]	DCPI (mm/blow)	S_{DCPI}[a]	CBR (%)	S_{CBR}[a]	PI (%)	γ_d (kN/m^{3})	W (%)	w_L (%)	p_{200} (%)
1	22.30	2.20	17.5	2.10	3.30	1.45	11.5	13.28	19.00	32.5	22.5
2	131.80	2.30	1.00	0.72	34.00	1.80	9.5	19.66	9.89	27.2	17.9
3	64.50	2.50	6.00	1.80	12.86	1.63	18.0	18.35	13.89	40.3	27.5
4	60.40	2.40	3.71	2.03	14.00	1.44	19.1	15.53	19.12	50.3	27.6
5	56.62	2.62	4.03	1.18	11.40	1.15	29.2	17.19	15.20	60.8	30.8
6	61.87	1.87	4.43	1.48	16.08	1.08	11.4	15.32	16.85	47.6	16.5
7	64.38	2.38	3.84	1.88	14.91	1.02	17.5	15.01	18.60	41.6	55.2
8	73.13	2.13	4.19	1.50	17.54	1.09	14.4	16.66	14.10	38.0	27.4
9	66.80	2.80	7.55	1.32	15.35	1.07	29.9	15.68	14.81	45.9	13.0
10	28.38	2.38	9.93	1.81	6.36	1.10	15.6	16.20	13.58	40.8	28.2
11	43.50	2.50	13.00	1.77	5.92	1.07	17.0	15.15	10.26	38.6	19.4

[a] S_{pfwd}, SD of E_{pfwd} values; S_{DCPI}, SD of DCPI values; S_{CBR}, SD of CBR values.

and the DCP readings. The best-fit curve obtained followed a logarithmic model as expressed in Equation (4) with an R^2 value of 0.82, an adjusted R^2 value of 0.81, a SE of 0.283 and an F-test value of 142.8. The p-value of the variable DCPI was less than 0.001%. This indicates that DCPI has a strong capability to explain the model variations. It may be noted from the data that the average penetration rate ranged between 1 and 18.3 mm per blow, and the observed CBR value varied between 3.9 and 50, respectively.

$$\mathrm{Log(CBR)} = 1.675 - 0.7852\,\mathrm{Log(DCPI)}. \quad (4)$$

The CBR and DCPI of a soil depend to a large extent upon the type of soil, the degree of compaction, the method of compaction, the dry density and the moisture content. The above relationship was developed based on the observations performed at field densities and field moisture contents. Alternatively, Equation (4) can also be transformed as in Equation (5).

$$\mathrm{CBR} = 47.32\,\mathrm{DCPI}^{-0.7852}. \quad (5)$$

This transformation will assist in obtaining the scatter plot and the best-fit curve relating the observed CBR values and the observed DCPI values as shown in Figure 2.

It also facilitates the comparison of actual and predicted observations for the CBR values as shown in Figure 3. Here, the regression line fits with an R^2 value of 0.83 and a negligible intercept of 0.0137. This regression line coincides satisfactorily with the 'theoretical line of equality' that passes through the diagonal.

The performance of the model developed in the present study was then compared to that of the models formulated by Gabr *et al.* (2000) using the data reported in this study. The logarithmic models were transformed and the CBR values were predicted based on the observed values of DCPI as shown in Figure 4. Through this exercise, it may be observed that the model developed in the present study for lateritic subgrades of Dakshina Kannada in India performed in a manner very close to that proposed by Gabr *et al.* (2000). However, for DCPI observations between 0 and 5, the behaviour of lateritic soils investigated as part of this study showed a marked difference when compared with that of Gabr *et al.* (2000).

6.2 *Correlation between PFWD and DCP observations*

Various families of curves were tested using SPSS for the given data for exploring the correlations between the PFWD and DCP readings. The power model as expressed

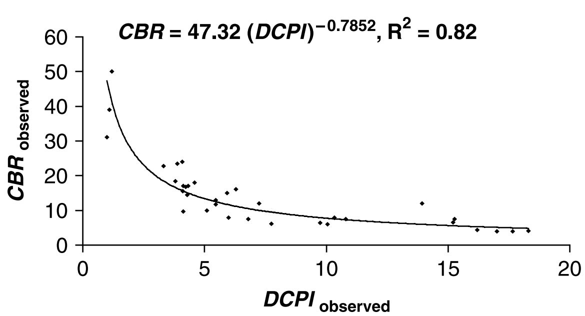

Figure 2. Plot of CBR vs. DCPI for observed values.

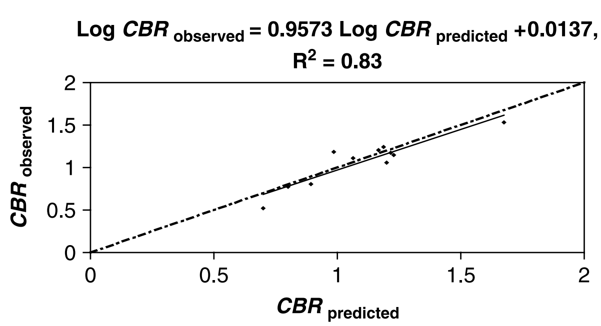

Figure 3. Comparison between observed and predicted CBR.

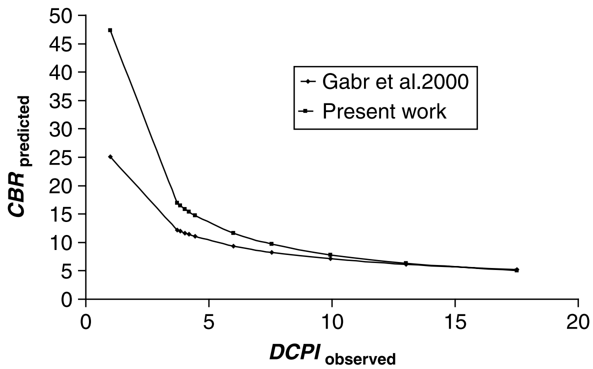

Figure 4. Comparison of model developed.

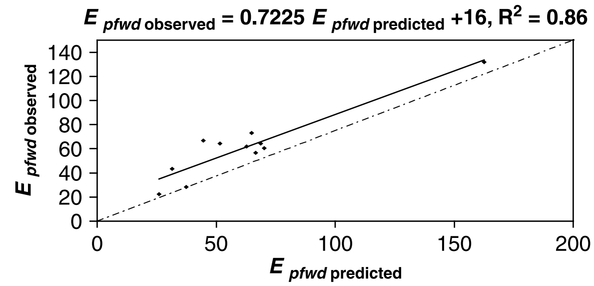

Figure 6. Comparison between observed and predicted E_{pfwd}.

in Equation (6) was identified as the best-fit curve. This relationship displayed a reasonably good correlation with an R^2 value of 0.73, an adjusted R^2 value of 0.72, an SE of 0.295 and an F-test value of 87.23. The p-value of the variable DCPI was lesser than 0.001%. This indicates that DCPI has a strong capability to explain the model variations. Here, the average penetration rate for the DCP tests ranged between 1 and 18.3 mm per blow and the modulus of elasticity observed using the PFWD ranged between 20 and 174.1. The above relationship was developed based on the observations performed at field densities and field moisture contents.

$$E_{\mathrm{pfwd}} = 162.48 \times (\mathrm{DCPI})^{-0.6397}. \tag{6}$$

The E_{pfwd} and DCPI of a soil depend to a large extent upon the type of soil, the degree of compaction, the method of compaction, the dry density and the moisture content. The scatter plot and the best-fit curve relating the observed E_{pfwd} values and the observed DCPI values are shown in Figure 5.

The scatter plot and the best-fit curve relating the observed E_{pfwd} values and the predicted E_{pfwd} values are shown in Figure 6. Here, the regression line fits with an R^2 value of 0.86 and an intercept of 16. This regression line lies reasonably close to the 'theoretical line of equality' that passes through the diagonal.

The performance of the model developed in the present study was then compared to that of the models formulated by Chen *et al.* (2005) using the data reported in this study as shown in Figure 7. Through this exercise, it may be observed that the model developed in the present study for lateritic subgrades of Dakshina Kannada in India performed in a manner similar to the models represented by Equation (2) (Chen *et al.* 2005).

7. Exploring the influence of geotechnical parameters on CBR and subgrade modulus

In addition to the above regression equations, Equations (7) and (8) developed as part of this study indicate that the values of the dry density (γ_d) for soil samples of different sites show a marked positive influence on the prediction of the E_{pfwd} and CBR values, while the liquid limit (w_L), the plasticity index (PI) and the moisture content (w) have a negative effect. The R^2 values for Equations (7) and (8) were 0.83 and 0.85, respectively, while the root mean-square error values were 15.81 and 4.2, respectively, and the F-test values were 34.93 and 41.37, respectively. The p-values for γ_d, PI, w and w_L in Equation (7) are 0.000, 0.073, 0.010 and 0.001, respectively. Similarly, the p-values for γ_d, PI, w and w_L in Equation (8) are 0.000,

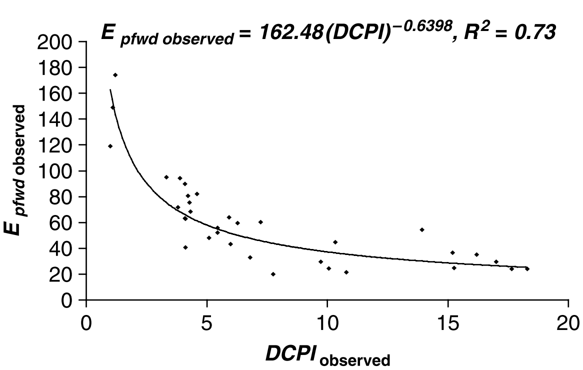

Figure 5. Plot of E_{pfwd} vs. DCPI.

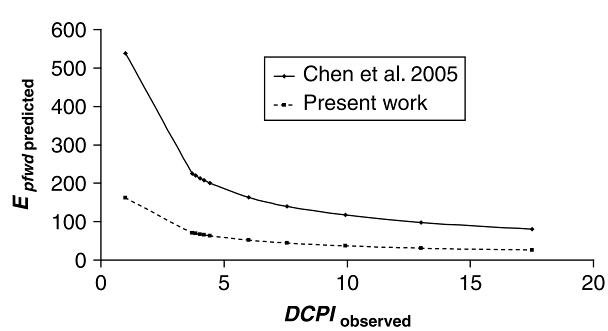

Figure 7. Comparison of models.

0.184, 0.003 and 0.000, respectively.

$$E_{\mathrm{pfwd}} = 94.928 + 4.704\gamma_{\mathrm{d}} - 1.096\mathrm{PI} - 2.954w - 1.237w_{\mathrm{L}}, \quad (7)$$

$$\mathrm{CBR} = 23.048 + 1.423\gamma_{\mathrm{d}} - 0.213\mathrm{PI} - 0.916w - 0.368w_{\mathrm{L}}. \quad (8)$$

8. Summary

The use of the PFWD, the DCP and the CBR assist road engineers in assessing the subgrade strength. Investigations on stiffer subgrades result in higher CBR and Epfwd values and lower DCPI values. This is reflected in the sign of the powers of the independent variables used in the regressions developed above (see Equations (5) and (6)). The values of the liquid limit, and the plasticity indices for the soil samples tested for various sites, varied between 12.5–57.20 and 3.68–31.2, respectively. Also, the percentage of soil fraction passing 75 μm sieve for the soil samples varied between 9.8 and 47.3.

The regression models discussed in Equations (5)–(8) enable the prediction of CBR values based on the observed values of average penetration rates of DCPs and the elastic moduli of the subgrade at the field density and the field moisture content. PFWD and DCP investigations in progress are shown in Figure 8.

Figure 8. Deployment of PFWD and DCP at site.

9. Conclusions

The important conclusions and findings of this study are listed below:

- The correlation between the CBR values and the penetration rates of the DCP (DCPI) for the lateritic soils of Dakshina Kannada district followed a logarithmic model of the form Log(CBR) $= a + b$ log(DCPI), where the coefficients '*a*' and '*b*' assume the values -1.675 and 0.7852, respectively. Alternatively, this expression can also be transformed into a power model of the form CBR $= 47.32$ DCPI$^{-0.7852}$. This transformation will assist in making comparisons with other studies performed in this area.
- The trend shown by the regression model for the prediction of CBR using DCP observations, developed for lateritic soils of the district of Dakshina Kannada, was found to agree with that of the model proposed by Gabr *et al.* (2000) for tests conducted at Raleigh, North Carolina, where the coefficients '*a*' and '*b*' assumed the values 1.4 and -0.55, respectively, for investigations on the distress state of subgrades overlaid with aggregate base courses.
- The model developed in this study between the E_{pfwd} values and the penetration rates of the DCP for the lateritic soils of Dakshina Kannada district followed a power model of the form $E_{\mathrm{pfwd}} = A \times \mathrm{DCPI}^{B}$, where the coefficients A and B assumed the values 162.48 and -0.6397, respectively. Alternatively, this expression can also transformed into a logarithmic model of the form $\mathrm{Log}(E_{\mathrm{pfwd}}) = 2.21 - 0.6397$ Log(DCPI). This transformation will assist in making comparisons with other studies performed in this area.
- The trend shown by the regression model for the prediction of E_{pfwd} developed for lateritic soils of the district of Dakshina Kannada was found to agree with that proposed by Chen *et al.* (2005).
- In addition to the above, it was observed that the dry density has a significant influence on the prediction of CBR and the E_{pfwd} values.

Notes

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