The 12th International Conference of
International Association for Computer Methods and Advances in Geomechanics (IACMAG)
1-6 October, 2008
Goa, India

PFWD, CBR and DCP Evaluation of Lateritic Subgrades of Dakshina Kannada, India

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Keywords: Subgrade, Portable Falling Weight Deflectometer, California Bearing Ratio, Dynamic Cone Penetrometer

ABSTRACT: The performance of pavements depends to a large extent on the strength and stiffness of the sub-grades. Among the various methods of evaluating the subgrade strength, the use of portable falling weight deflectometers (PFWD) is gaining popularity in the recent years. This is due to its simplicity in design, portability, and the added advantages of providing quick and reliable estimates of the Young's modulus of elasticity of pavement subgrades. Hence it was felt that there is a need to study the correlation between results obtained using the PFWD and those obtained using the traditional approaches such as the California bearing ratio (CBR) test, the dynamic cone penetrometer (DCP) test. The work described herein focuses on exploring the correlations between the results obtained using the PFWD, and the results obtained using the CBR method and DCP for lateritic soils at various locations of Dakshina Kannada district of the State of Karnataka, India. Regression models were developed as part of this study to enable the prediction of CBR values based on the average of observed values of the Young's modulus obtained using the PFWD (E_{pfwd}), and prediction of E_{pfwd} from the average penetration-rates of DCPs performed for field density, and field-moisture content.

1 Introduction

Roads have performed a very useful role in meeting the strategic and developmental requirements, accelerating all-round development. Technological progress in road construction technology has kept pace with rapid changes in the field of infrastructural development. The world has witnessed the engineering excellence of India in various fields of Civil Engineering including road construction, and the capability of our engineers in adopting a scientific approach towards solving challenging problems.

Sub-grades play an important role in imparting structural stability to the pavement structure as it receives loads imposed upon it by road traffic. Traffic loads need to be transmitted in a manner that the subgrade-deformation is within elastic limits, and the shear forces developed are within safe limits under adverse climatic and loading conditions. The sub-grade comprises unbound earth materials such as gravel, sand, silt and, clay that influence the design and construction of roads. The assessment of properties of soil sub-grades, in terms of density, soil-stiffness, strength, and other in-situ parameters is vital in the design of roads, and their performance.

Traditionally, flexible pavements are designed based on the CBR approach or by considering elastic deformations. The CBR approach to pavement design gained popularity among practicing engineers in the late 1980s with the use of advanced computing power and speed (Rollings 2003). But this approach to flexible pavement design, gives more importance to the estimation of the density of the sub-grades and the pavement layers. Other design philosophies for flexible pavement do exist, including those with more of a basis in the theory of the mechanics of materials—such as layered elastic and finite element approaches. In the classical approach to design of flexible pavements using the Burmister's (1958) layer theory, it is required to estimate the elastic modulus of the sub-grade in order to determine the required layer-thickness of a pavement structure.

Despite the advances in these state-of-the art approaches to pavement design, the CBR approach continues to be one of the most reliable methods for pavement design, especially in the design of pavements for military and civilian aviation (Semen 2006). This method is supported by more than 60 years of field experience under a wide range of conditions throughout the world. In addition to this, the approach to quality control of pavements gives more importance to 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.

Of the various methods of evaluating the sub-grade strength, the use of alternative techniques including non-destructive approaches to pavement evaluation such as the use of portable falling weight deflectometers (PFWD) is gaining popularity. This is due to their inherent capability in obtaining quick estimates of the Young's modulus of the subgrade in addition to their simplicity of design. The use of dynamic cone penetrometers (DCP) has also become wide-spread since they can be easily fabricated, and they facilitate rapid testing and evaluation of subgrades based on the resistance offered to penetration. In view of the new developments in the field of pavement evaluation, there exists a need to correlate the results obtained by using PFWDs to those obtained using traditional approaches such as the CBR and DCP for the benefit of road engineers. This work focuses on exploring the correlations between these approaches for lateritic soils of Dakshina Kannada district, India

1.1 Necessity for Correlating Subgrade Modulus to CBR and DCP Observations

Pavement evaluation relies mainly on information on the stiffness of pavement layers, and the modulus of subgrades as references, in addition to supplementary data on density and moisture content. It is often required 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, labor-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.

Modern devices such as the falling weight deflectometers (FWD), GeoGauges, dirt-seismic pavement analyzers (DSPA), and laboratory-based repetitive tri-axial tests are used to estimate the modulus of elasticity of pavement layers (Nazarian et al., 2002; Livneh and Goldberg, 2001; Rahim and George, 2002; and Sawangsuriya et al., 2002). But each of these devices has its advantages and disadvantages. The use of FWDs require the deployment of trained personnel in addition to heavy investments although the results are reliable, while the use of laboratory-based repetitive tri-axial tests is not generally adopted due to cumbersome procedures in addition to the need for skilled professionals (Rahim and George, 2002; Chen et al., 2001). In comparison to the above, analysis using dirt-seismic pavement analyzers (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 analyzed, and is considered to provide a composite-stiffness that includes the effect of all layers up to an un-specified depth (Chen et al., 2005). But the invention of the portable falling weight deflectometer (PFWD) has revolutionized the field of pavement-evaluation mainly due to its simplicity, ease of use, portability, reliability, and ruggedness.

In this connection, it may also be noted that a number of road construction authorities employ the traditional approach to pavement evaluation using the California bearing ratio test. Though this approach to pavement design is criticized for being an empirical design method, the results of this once popular method, is supported by more than 60 years of field experience, under a wide range of conditions throughout the world. But Huang (1993) justifies that ‘dependence on observed performance is necessary because theory alone has not proven sufficient to design pavements realistically’. The CBR method, thus still serves as the foundation for the design of flexible and un-surfaced pavements and their evaluation, particularly in circumstances where ‘expedient and contingency evaluation’ of ‘military airfield pavements’ (Davit et al. 2002).

But recently, there is a preference among road-engineers to adopt simpler, faster and more reliable methods of pavement evaluation, the results of which can correlate with the CBR test (Al-Amoudi et al., 2002), which is the most widely adopted traditional approach to pavement evaluation. Due to this reason, it is essential to correlate the results obtained through the CBR method, to that obtained using the FWD or PFWD (FAA, 1995; Barter et al., 1975). Also, according to the manufacturers of non-destructive testing equipment, the relationships between the CBR values and the moduli of elasticity are dependent upon the local geology (Phillips 2005).

The use of falling weight deflectometers (FWD) and portable falling weight deflectometers (PFWD) can be considered to be more effective in pavement evaluation in this scenario. The use of non-destructive testing devices such as PFWDs will assist highway engineers in assessing the elastic modulus of local soils, and subgrades more reliably, rapidly, and in a more cost-effective manner.

A study on this topic reveals that a number of correlations have been developed between the DCP observations and the CBR values, but the lack of information on correlations between the modulus of subgrades to the results obtained using the DCP, and the CBR, has acted as a stumbling block in the wide-spread adaptability of this approach to pavement evaluation by the pavement-engineering community (Chen et al., 2005). This work focuses on exploring reliable correlations between the results of the CBR and DCP to the modulus of elasticity estimated using the PFWD especially for lateritic soils of Dakshina Kannada district of India.

2 Review of Literature

The following provides a brief overview of literature on correlation-studies for investigations based on the *CBR, DCP, and PFWD* observations.

2.1 Correlations with Subgrade Modulus to DCP and CBR Observations

This section provides information on the development of correlations between observations of the subgrade modulus, and the CBR, and DCP observations. Powell et al. (1984) proposed the most widely accepted relationship between the CBR value and the modulus of the subgrade (*Es*) measured in MPa as given in Eq.1,

$$Es = 17.58 \times CBR^{0.64} \quad (1)$$

Nazzal (2003) reported details of studies on correlating the CBR values to the elastic modulus measured using the Prima 100 LFWD (E_{pfwd}), and developed an expression as given in Eq.2. This relationship was developed for E_{pfwd} values ranging between 2.5 and 174.5 MPa, and had an R-square value of 0.83.

$$CBR = -14.0 + 0.66\,(E_{pfwd}) \quad (2)$$

Seyman (2003) has reported the use of relationships developed by Pen (1990) where the back-calculated layer-moduli (*Es*) of pavements measured in MPa can be estimated using the penetration-rate (*DCPI*) of DCP tests as in Eq.3, and Eq.4 where the calculation of the layer-moduli was performed using the Phoenix system, and the Peach system respectively. The R-square values of these relationships developed were 0.56 and 0.81 respectively.

$$\text{Log } Es = 3.250 - 0.89 \log (DCPI) \quad (3)$$

$$\text{Log } Es = 3.653 - 1.17 \log (DCPI) \quad (4)$$

De Beer (1990) proposed a simple correlation of R-square value of 0.76 between the back-calculated elastic modulus (*Es*) determined using a Heavy Vehicle Simulator, and the penetration index (*DCPI*) expressed in mm per blow as expressed in Eq.5 based on 86 observations:

$$\text{Log } (Es) = 3.05 - 1.07 \text{ Log } (DCPI) \quad (5)$$

Webster et al. (1992) have reported the development of a relationship between the *CBR* value and the penetration rate (*DCPI*) expressed in mm per blow as in Eq.6 by the U.S. Army Corps of Engineers for a wide range of granular and cohesive materials. This correlation has been adopted by many researchers (Livneh, 1989; Webster et al., 1992; Seikmeir et al., 1999).

$$\text{Log } CBR = 2.465 - 1.12 \text{ Log } (DCPI) \quad (6)$$

Chen et al. (2005) have reported studies conducted by AASHTO (1993) for the design of pavements where a correlation model as in Eq.7 was developed for the determination of the modulus of elasticity (*Es*) 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.

$$Es = 10.34 \times CBR \quad (7)$$

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) as in Eq.8.

$$Es = 664.67 \times DCPI^{-O.7168} \quad (8)$$

Further studies by Chen et al. (2005) using DCPs and FWDs for roads in Texas provided correlations connecting the layer-moduli (*Es*), and the penetration-rate (*DCPI*) measured in mm per blow for DCP tests, as expressed in Eq.9. This relationship had an R-square value of 0.855 and a mean-square error of 0.15.

$$Es = 537.76 \times DCPI^{-0.6645} \quad (9)$$

Fleming et al. (2000) conducted field tests correlating the observations of the moduli of subgrades obtained using the falling weight deflectometer to the results obtained using the light falling weight deflectometers (LFWD), and portable falling weight deflectometers (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 to the values estimated by Prima 100 LFWD ($E_{lfwd\text{-}Prima\ 100}$) as observed in Eq.10. However, the values estimated using the GDP (E_{GDP}), and the TFT (E_{TFT}) were comparatively less consistent as evident in Eq.11, and Eq.12.

$$M_{FWD} = 1.031\, E_{lfwd\text{-}Prima\ 100} \quad (10)$$

$$M_{FWD} = 1.05 \text{ to } 2.22\, E_{GDP} \quad (11)$$

$$M_{FWD} = 0.76 \text{ to } 1.32\, E_{TFT} \quad (12)$$

Nazzal (2003) also conducted studies on correlating back-calculated resilient moduli values (M_{FWD}) obtained using FWDs to the estimated values of the modulus of subgrade (E_{lfwd}) obtained from observations using LFWDs. Eq.13 provides a very high correlation between the values at an R-square value of 0.94, at a significance level of lesser than 99.9%, and a standard error of 33.1. The relationship was developed for observations of elastic moduli estimated using LFWDs within the range of 12.5 to 865 Mpa.

$$M_{FWD} = 0.97\,(E_{lfwd}) \quad (13)$$

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 to the DCP and CBR readings. This would be of special advantage to road-engineers of developing nations, and lesser developed countries. The Inspector-2 PFWD manufactured by Englo, of Estonia was used in the present study for the estimation of the subgrade moduli.

3 Working of the DCP

The Scala penetrometer, also known as the Dynamic Cone Penetrometer, was developed in 1956 in South Africa as an in situ pavement evaluation technique for evaluating pavement layer strength (Scala 1956). This device consists of a steel rod with a steel penetration cone of 60 degrees 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 is measured using a calibrated scale. It is possible to measure up to 800 mm depth of penetration. However, it is also possible to measure penetrations of up to 1200 mm depth when fitted with an extension rod. Using this device, we can measure the subgrade strength in terms of penetration in millimeters 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 stabilized soils. A number of studies have been performed to correlate the results of the DCP test for the estimation of in-situ California Bearing Ratio (CBR).

4 Working of PFWDs

Falling weight deflectometers (FWD) are in-situ testing devices initially developed in Germany as an alternative to the plate load test. The light-weight versions of this device, known as the light-falling weight deflectometer (LFWD), or the portable falling weight deflectometer (PFWD) came to be used extensively in the Middle East, Japan, Europe, and the United States (Nazzal, 2003). The LFWDs, and PFWDs developed include the German Dynamic Plate (GDP), the TRRL Foundation Tester (TFT), and the Prima 100 LFWD, and the more efficient PFWDs such as the Loadman (Gros, 1993), Inspector-2 (see Fig.1), and Zorn ZFG 2000.

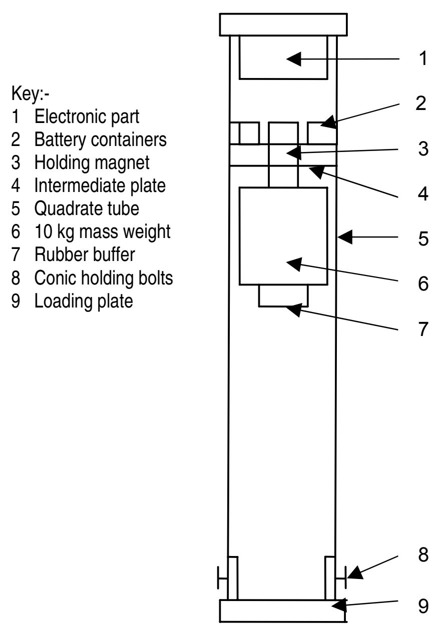


Figure 1. Inspector-2 PFWD

Portable falling weight deflectometers (PFWD) are provided with accelerometers in place of geophones as used in FWDs. The PFWDs are equipped with holding magnets that hold the falling weight at a specific height. In these devices, the Young's modulus is automatically determined by the embedded software, and 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. PFWDs are equipped with two types of circular loading plates, one of 140 mm, and the other of 200 mm diameter. The plate of 140 mm diameter is used for soils with Young's modulus varying from 10 Mpa to 1200 MPa. The plate of 200 mm diameter is used for soft soils where the Young's modulus is estimated to be lesser than 10 MPa, and where the deflections are observed to be more than 5 mm when tested with the plate of 140 mm diameter. The PFWDs are relatively cheap, and can be easily transported. PFWDs also assist in obtaining quicker measurements of various soil characteristics.

5 Details of the PFWD, DCP and CBR Tests Performed

The investigation was aimed at conducting tests at 50 locations along National Highway NH-17, between New Mangalore Port Trust, and Mulky of Dakshina Kannada district, India. The PFWD observations were made on natural soil subgrade after removing the loose top-soil for a depth of 300 mm. Eight observations were recorded at each location, and the average value was reported as the modulus of elasticity for that site (E_{pfwd}). The readings were taken randomly for points 300 mm away from the edges of the pit and towards its center. Tests using the dynamic cone penetrometer were then conducted at these locations immediately after the PFWD tests were completed. The number of blows required for a penetration of 300 mm after application of the seating load of one blow 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 reported.

Core samples of soil from each of the above locations were collected, and the field moisture-content and field density were determined. The soil samples were then air-dried before performing the CBR tests on these in the laboratory. After determining the quantity of soil required to fill the standard CBR mould for the field density, the CBR-mould was filled by compacting soil in three equal layers. The CBR test was then performed for the field density, and the field moisture content according to specifications (IS: 2720-Part 16, 1979), and the readings were measured.

6 Results and Discussion

The details of the observations for investigations conducted using the PFWD, the DCP, and the CBR for various locations were noted. The CBR value (expressed in percentage), the dynamic cone penetrometer index (expressed in mm/blow), and the Young's modulus as obtained using the PFWD (expressed in MPa) were subjected to statistical analysis using SPSS.

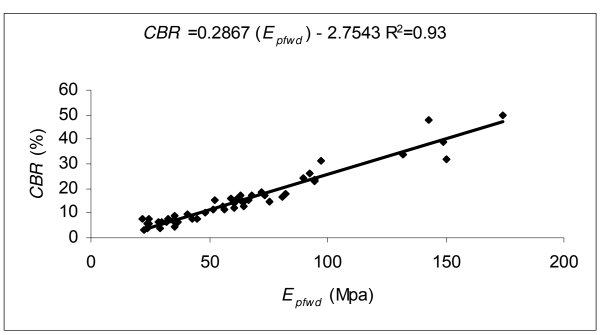
6.1 Correlation between PFWD and CBR Observations

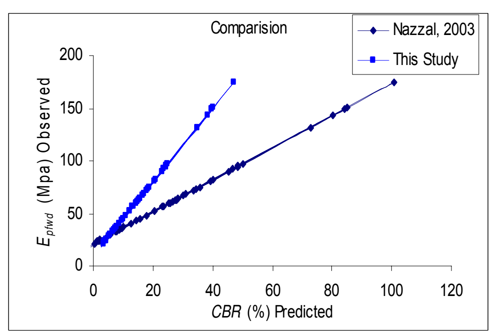
A relationship connecting the observations for the CBR and PFWD tests was developed based on site investigations conducted for the district of Dakshina Kannada, India where the subgrade soil is predominantly lateritic in nature. Eleven families of curves were tested for the data using SPSS, and the best-fit curve obtained was found to follow a linear model as expressed in Eq.14 with an R-square value of 0.96, an adjusted R-square value of 0.93, a standard error of 2.74, and an F-test value of 712.18. The high R-square value represents the closeness of data observed to the regression model. The dispersion of the observed values about the regression line is represented by the sum of square of errors, while the F-test evaluates the strength of the relationship between the dependent and independent variables.

$$CBR = -2.7543 + 0.2867\,(E_{pfwd}) \qquad (14)$$

The above relationship was developed based on observations performed at field-densities and at field-moisture contents. The scatter plot and the best-fit curve relating the observed CBR values and the observed E_{pfwd} values are provided in Fig.2 (a).

The performance of the model developed in the present study was then compared to that of the model formulated by Nazzal (2003) using the data obtained in this study as shown in Fig.2 (b). 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 Eq.2 (Nazzal. 2003).





(a) (b)

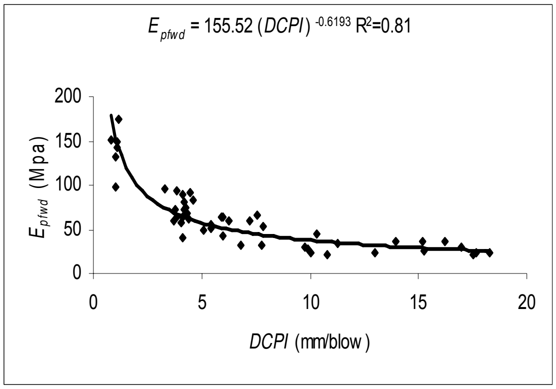
Figure 2. Scatter plot between *CBR* and E_{pfwd} values

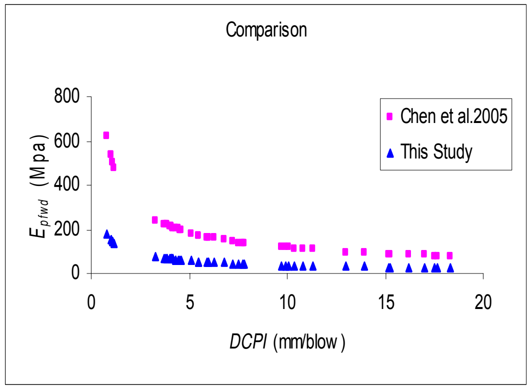
6.2 Correlation between PFWD and DCP Observations

In order to explore correlations between the PFWD, and DCP readings, various families of curves were tested for the data. The power model as expressed in Eq. 15 was identified as the best-fit curve. This relationship displayed a reasonably high correlation with an R-square value of 0.81, an adjusted R-square value of 0.80, a standard error of 0.244, and an F-test value of 204.81 at a significance level of 99.9%. The above relationship was developed based on observations performed at field-densities and at field-moisture contents.

$$E_{pfwd} = 155.52 \times (DCPI)^{-0.6193} \quad (15)$$

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 provided in Fig.3.





(a) (b)

Figure 3. Scatter plot between *DCPI* and E_{pfwd} values

The performance of the model developed in the present study was then compared to that of the model formulated by Chen et al. (2005) using the data reported in this study as shown in Fig.3. 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 model represented by Eq.9 (Chen et al., 2005).

7 Summary and Conclusions

The performance of pavements and their service-lives depend to a large extent on the subgrade characteristics. The subgrade characteristics play a major role in the selection of materials for the sub-base and the base courses of pavements. Hence, the evaluation of the subgrade strength assumes great importance in pavement design. The values of the CBR, the penetration-rate of DCPs, and the E values determined using the PFWD depend on the subgrade characteristics.

Models developed as part of this study will enable the prediction of CBR values based on observed values of the elastic moduli of the subgrade at the field density and at the field-moisture content. Firstly, the model developed correlating the CBR observations to the PFWD values was compared to those formulated by Nazzal (2003). Secondly, model developed correlating the PFWD observations to the DCP values was compared to those formulated by Chen et al. (2005). The important conclusions and findings of this study are listed below:

- The model developed in this study between the CBR values and the E_{pfwd} values measured by PFWD for the lateritic soils of Dakshina Kannada District followed a linear model of the form, $CBR = A \times (E_{pfwd}) - B$ where the coefficients A and B assume the values 0.2867 and 2.7543 respectively and this model found to agree to the pattern of model proposed by Nazzal. (2003).
- 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, $E_{pfwd} = A \times DCPI^{B}$, where the coefficients A and B assume the values 155.52 and -0.6193 respectively and this model found to agree to the pattern of model proposed by Chen et al. (2005).
- The models developed from this research is very much useful to the field engineers working with laterite soils of this region as E_{pfwd} observations are very quickly performed and CBR at field condition can be predicted on the spot.

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