International Journal of Scientific Research & Engineering Trends
Volume 9, Issue 4, Jul-Aug-2023, ISSN (Online): 2395-566X

Effective Utilization of CBR and Plate Load Test to Analyze the Strength of Pavements

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Abstract- Using California Bearing Ratio (CBR) tests and finite element modelling (FEM), this study details the process of determining the elasticity modulus (E) and the subgrade response modulus (ks). Cosmos works FEM model represents the soil, the load plunger, and the steel Mould of CBR, simulating the pressure-displacement reaction of the soil in the CBR Mould. The California Bearing Ratio (CBR) is positively correlated with the Modulus of Elasticity (E).created using the soil's elasticity as a starting point. In addition, a link is postulated between E and CBR. The modulus of subgrade response may be determined from E values and vice versa. Foundation design, soil structure interaction, highway formation design, etc. all rely on knowing the modulus of subgrade response, and the CBR test is thought to make this task easier.

Keywords- Subgrade, Plate Load Test, California Bearing Ratio (CBR), Pavement Design, Flexible Pavements, Soil- Structure Interaction.

INTRODUCTION

Effective highway construction relies on meticulously preparing the subgrade layer, which serves as the foundational base for pavements. An essential aspect is assessing the subgrade's quality during both construction and preparation phases. The California Bearing Ratio (CBR) test stands as a prevalent tool in highway and runway design, gauging soil suitability for subgrades or subbases. Additionally, field plate load tests ascertain the modulus of subgrade reaction (ks) and soil deformations, crucial for foundation design, soil-structure interaction research, and various roadway pavements, whether flexible or stiff.

The measurement of ks-value during field plate load tests, a representation of the modulus of subgrade response, is integral, with the Minnesota Department of Transportation (MnDOT) furnishing extensively used ks-values for pavement design models. However, these plate load tests demand substantial resources in terms of time and finances. Moreover, performing them effectively at depths exceeding 1 or 2 meters below ground level poses challenges.The interplay between the CBR test and plate load test is evident in their analogous nature. In both, the soil sample yields under weight, with gradual loading of the plate at the desired depth below ground. Plates, be they round, square, or rectangular, ranging in diameter from 300 millimeters to 760 millimeters, are utilized. The CBR test’s purpose aligns with that of the plate load test in calculating the field load-settlement curve of the soil.

This synthesis of the CBR test and plate load test extends to calculating the ks-value. To enhance the integration of these two formerly disparate tests, correlated links between CBR and E, and subsequently CBR and ks, are developed. This connection fosters a more cohesive relationship, improving highway engineering and foundation engineering's use of CBR values and KS-based design methodologies.

A robust transportation network is imperative for any nation's rapid growth, facilitating interconnection and accessibility across regions. Governments globally invest extensively in infrastructure, including the Pradhan Mantri Gram Sadak Yojana (PMGSY) in India, aimed at enhancing rural communities' all-season road access. Encompassing millions of kilometers of new paving and resurfacing, the initiative underscores safety and connectivity. Challenges arise from a significant portion of India’s clay- rich soils, necessitating careful pavement design due to soil expansion and contraction. Notably, flexible pavements offer advantages in terms of installation costs and maintenance ease.

However, paving on clay subgrades demands comprehensive strategies to avert premature failures. Whether flexible or stiff, pavement types bring their own set of considerations to address the diverse subgrade soils encountered in the construction process.

II. FAILURES IN FLEXIBLE PAVERS OVER CLAY SUBGRADES)

1. Subgrade Failures and Challenges:

Rainy seasons impact subgrade soil by softening it, leading to penetration into the sub foundation, causing flexible pavements to break. Expansive soils expand excessively and weaken under wet conditions, necessitating thicker pavements, which escalate building costs. Cyclical expansion and contraction due to precipitation changes also destabilize roadways, leading to instability and shoulder shear failures, particularly on single-lane highways with expansive soil subgrades.

2. Pavement Deterioration:
The soil along driveway edges softens during wet months, causing noticeable deformations and undulations in pavement due to tire tracking. Subsoil infiltration during wet weather leads to subgrade-pavement mixture, diminishing pavement thickness until it can't support weight. Rain-induced subgrade moisture scouring leads to bitumen degradation, causing raveling in aggregate.

3. Volume Instability and Subgrade Challenges:
Wet season subgrade soil softening and subbase penetration into softened subgrade indicate volume instability. With a significant portion of India consisting of clay soils, research is needed. Pavements on clay subgrade suffer from ruts, fractures, and potholes. Sidewalks on clay subgrade are inadequate for bicycles.

4. Geosynthetics for Subgrade Improvement:
Academics have focused on geosynthetics in the past two decades. Using geosynthetics as separators between subgrade and base material can enhance pavement performance, preventing deterioration caused by subgrade- soil interaction. Geotextiles and geogrids improve subgrade performance through separation, load distribution enhancement, and tensioned membrane effect. Various soil stabilization methods exist, including pre-wetting, cohesive soil cushions, and moisture barriers, but none aim to reduce pavement depth.

This research aims to construct flexible pavements on expanding and non-expanding clay subgrades, seeking effective design approaches to address instability and thickness challenges while assessing test track performance under traffic and weather conditions.

III. A LITERATURE REVIEW

1. Subgrade Significance and Issues:
The chapter reviews the importance of subgrade in pavement design, particularly concerning expansive soils and their treatment. Geotextiles and geogrids' utilization for sidewalk construction is explored. While coarse-grained soils are suitable for sidewalks, fine-grained ones, especially clayey soils, pose challenges. Pavement failure results from deformations in clayey soils due to densification and recurring stress.

2. Subgrade and Pavement Interaction:
The subgrade's role, akin to a foundation's depth, is pivotal for road pavement stability and vehicle load transport. Soil- bearing capacity is determined through plate-load testing, such as Das's field test, which affects pavement design. Issues at sidewalk margins due to frequent moisture changes are observed, impacting surface deformation. Soil's hardening capacity influences surface deformation, particularly along the outer route that faces more wear and tear.

3. Expansive Soil Challenges:
The expansion and contraction of expansive soils pose challenges for civil engineering structures, with expansive clay soils covering a significant portion of India's roads. Expansive soils' constant behaviour changes lead to issues like sidewalk fractures, erosion, and subgrade migration, leading to accelerated pavement failure.

4. Subgrade Response and Correlations:
The modulus of subgrade response (ks), analogous to the coefficient of elastic uniform compression (Cu), affects soil deformation under pressure. Empirical correlations between modulus of elasticity (E) and compressive strength (CBR) are studied. Researchers propose a systematic link between CBR and E, utilizing finite element simulations to establish a causal relationship, facilitating soil-structure interaction and pavement investigation.

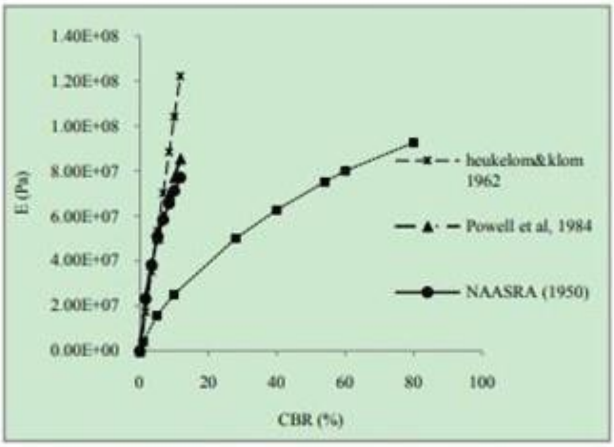


Figure 2. California Bearing Ratio versus Modulus of Elasticity

Heukelom and Klomp (1962) studied the correlation of CBR with E and proposed on empirical relationship as,

$$E = 1500 \ CBR \ (Psi) \tag{1}$$

This correlation is only for fine grained non expansive soils with a soaked CBR < 100% (AASHTO, 1993). Moreover, Powell et. al (1984) proposed a correlation of the CBR with E as,

$$E = 17.6 \ CBR^{0.64} \ (MPa) \tag{2}$$

Thus, the correlation between E and CBR developed by NAASRA (1950) has been divided into two parts.

For CBR less than 5,

$$E = 16.2 \ CBR^{0.7} \ (MPa) \tag{3}$$

Then, for CBR more than 5,

$$E = 22.4 \ CBR^{0.5} \ (MPa) \tag{4}$$

IV. METHODOLOGY

The pressure-response relationship for the CBR test is modelled in FEM. In order to construct the finite element model, we turned to Cosmos work Solid Work 2005. The input for the Cosmos works CBR mould model specifies steel for the base plate, cylinder mould, and load plunger.

The subgrade soil's structural qualities were needed as an input. Density, modulus of elasticity, and Poisson's ratio are the three. Elastic materials are thought to have a Poisson's ratio between 0.2 and 0.4. Poisson's ratio is often utilized at a value of 0.5 for saturated soils and a value of 0 for dry soils. Although the elastic responses of the medium are not very sensitive to variations in the value of Poisson's ratio (Bowles, 1984), it is frequently assumed due to the difficulty in determining it in the laboratory or in the field.

So, while it might range from 0 to 0.5, this variable has a negligible impact on the soil's elastic response (Harr, 1966; Kameswara Rao, 2000). To determine the load deflection curves, a finite element analysis was performed using values of E (modulus of elasticity) ranging from 1.00E+6 Pa to 1.00E+7 Pa. The CBR value is calculated according to BS 1377:1990, which specifies a load penetration of 2.5 mm of the CBR plunger (with a diameter of 50, 8 mm).

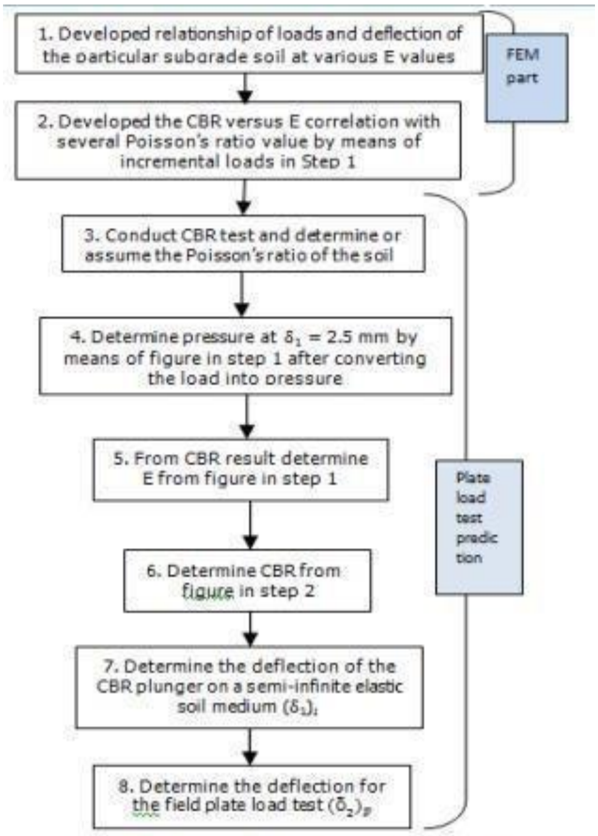

1. Developed relationship of loads and deflection of the particular subgrade soil at various E values
2. Developed the CBR versus E correlation with several Poisson's ratio value by means of incremental loads in Step 1
3. Conduct CBR test and determine or assume the Poisson's ratio of the soil
4. Determine pressure at $\delta_1 = 2.5$ mm by means of figure in step 1 after converting the load into pressure
5. From CBR result determine E from figure in step 1
6. Determine CBR from figure in step 2
7. Determine the deflection of the CBR plunger on a semi-infinite elastic soil medium $(\delta_1)_i$
8. Determine the deflection for the field plate load test $(\delta_2)_p$

Figure 3. Flow chart of the procedure to predict the PLT result

A vertically loaded plunger in elastic layers can have its response characterized by finite element analysis. Even though the mould is quite stiff in practice, the FEM analysis shows that the CBR plunger's centre and periphery experience varying degrees of deflection. Using the analytical findings provided by Tsytovich (Harr, 1966 results), the elastic analysis has been rectified to that corresponding to stiff analysis, allowing a correlation between the finite element result and the CBR test in the laboratory. Accordingly, the correction findings of Tsytovich (Harr, 1966) are applied to the centre deflection of the plunger to produce the appropriate deflection of the stiff plunger. Therefore, to get the relevant value of the deflection of the stiff plunger of the CBR mould transmitting the load to the soil, the deflection at the centre of the circular-shaped loaded region of the CBR plunger should be multiplied by the influence factor K = 0.79 (=/4) as per Tsytovich. As shown in Figure 3, a correlation approach between CBR and E and CBR and the plate load test has been designed.

V. RESULT AND DISCUSSION

CBR Parameter The usual outcome of a CBR test is shown in Figure 4. It demonstrates that the soil sample deflected more noticeably at increased loads. The typical procedure for obtaining the graph of mean bearing pressures vs mean settlement yields results that are consistent with this pattern. Figure 4 depicts the reaction of the soil subgrade structure to the applied load in a tightly restricted CBR mould, as seen by the deflection caused by the application of the load plunger. The CBR calculated from these numbers is 5.5%, which is in accordance with BS 1377-1990.

Finite-Element Analysis, Section 4.2. Figure 4 shows the location in the CosmosWorks Finite Element Model where the CBR mold model was created. Figure 4(a) and 4(b) show the CBR mould state in the Cosmoswork model and the solid mesh condition of the model, respectively; the input specifies that the base plate, cylinder mould, and load plunger all be made of steel.
Figure 6 displays the resultant connections between load and deflection for subgrade soils with varying E values. Figure 6 demonstrates that, for a given load, a higher value of the modulus of elasticity results in a smaller deflection. At 2.5 mm deflection, values of load are calculated over a range of E.

However, a comparable result to that shown in result 5 may be obtained by developing a correlation using the CBR value corresponding to a 5 mm deflection of the plunger, using the method described below. After that, the CBR value was estimated at the required plunger displacement of 2.5 mm (BS 1377-1990). However, the CBR test findings in Figure 6 are only valid for homogenous elastic media. To get the relevant value of the deflection of a rigid body transferring the load to the earth, the analysis of Tsytovich, as mentioned in Sections 3 and 4, must be rectified with the influence factor, K.The Association between CBR and E Adjusting the load against deflection findings in Figure 4 by multiplying by the correction factor of 0.79 yields the correlation of CBR versus E, which is then used to determine the necessary load to achieve a deflection of 2.5 mm when conducting CBR testing. In addition, E's value will be calculated at the designated load. As a result, we can calculate the relationship between CBR and E.

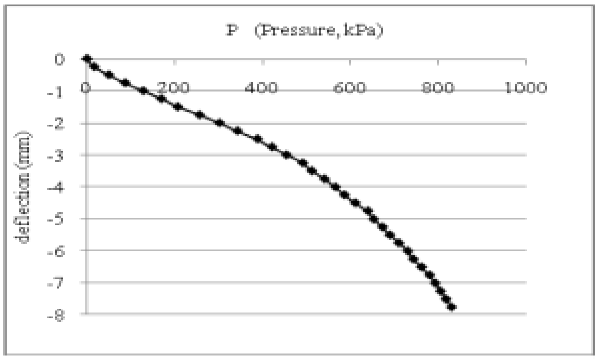
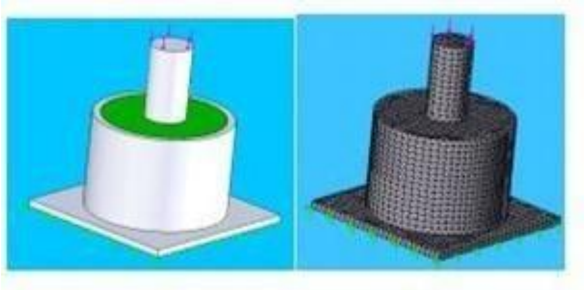


Figure 4. Result from CBR test



(a) CBR mould model (b) FEM mesh of the model

Figure 5. CBR mould in CosmosWorks

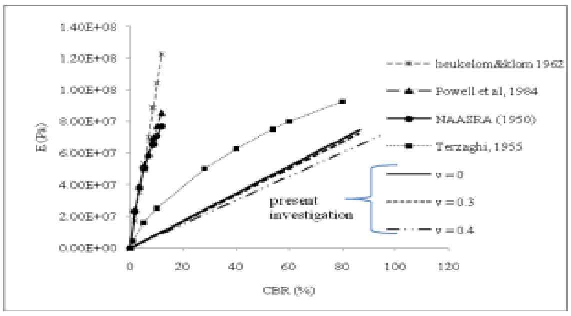


Figure 7. CBR versus E obtained from the FEM with various of Poisson's ratio

The correlation result from present study is close to the result from Terzaghi (1955) while the correlation made by Heukelom and Klomp (1962), NAASRA (1950) and Powell, Potter, Mayhew and Nunn (1984) differ considerably probably due to their empirical nature.

From Figure 7, the correlations between E and CBR from the present investigation are as follows,

$$E = 863.82 \text{ CBR (kPa)}, \quad \upsilon = 0 \qquad (5)$$

$$E = 840.53 \text{ CBR (kPa)}, \quad \upsilon = 0.3 \qquad (6)$$

$$E = 751 \text{ CBR (kPa)}, \quad \upsilon = 0.4 \qquad (7)$$

Figure 5 shows that the load at a deflection of 2.5 mm is 939.2 N for an elastic modulus of E = 3.00E+06, and the corresponding CBR value according to BS 1377-1990 is 7.1%. After adjusting the data reported in Figure 6 for stiff plunger deflection, the correlations of CBR vs. E are shown for different values of E of soil in Figure 7. Other people's correlations are included for reference as well.

VI. CBR TEST FOR THE PREDICTION OF THE PLATE LOAD TEST RESULTS

The bearing capacity and settlement of the soil, as well as the ks (modulus of subgrade response) value, are both determined by plate load tests; the ks value is the ratio of the pressure exerted to the settlement on the soil. The plate is then loaded incrementally and set at the intended foundation level. Plates can be round, square, or rectangular (Jones, 1997; Moayed and Janbaz, 2009) and range in size from 300 mm to 760 mm in diameter. Similar to the goal of the plate load test, the CBR test may be performed to get the load-settlement curve of the soil in the field.

Using this method, we will see how to calculate ks using the CBR test. Subgrade Reaction Modulus (ks) The clayey sand soil depicted in Figure 3 has a CBR value of 5.5%, according to the data. If the Poisson's ratio of the soil is 0.4, the established correlation yields the modulus of elasticity, E = 751 CBR (kPa), as shown in Figure 6.

E = 4751.01 kPa makes sense, then. Then, the theory of elasticity solution for a rigid plate on a semi-infinite elastic soil medium under a concentrated load (Timoshenko and Goodier, 1951; Harr, 1966; Kameswara Rao, 2000) may be used to derive an equation for the modulus of subgrade response, ks. as, The E value can also be calculated directly from the graph of the CBR test's results.

Figure 8 shows the result of the CBR test seen in Figure 4, with the abscissa converted to a pressure in kPa, inserted into Figure 6. Therefore, at a deflection of 2.5 mm, the modulus of elasticity, E, of clayey sand soil is around 3900 kPa. Equation (8) yields a value of 116535.52 kN/m3 for ks. Knowing the value of E of the soil, which can be determined from the CBR using equation (8), allows one to calculate the value of ks for any size, shape, and stiffness of plate.

Predicting Plate Load Test Response Predicting the elastic response of a plate using the CBR test result provides useful information. Because the CBR test and the field plate load test are so similar in methodology (except for the CBR test's boundary restraints), the CBR test can be used as a model to predict the field plate load test by transforming the result of the confined boundary of the CBR test into the responses of the CBR plunger (model plate) on a semi- infinite elastic medium.

$$k_s = 1.13 \quad \frac{E}{(1-\nu^2)} \; \frac{1}{\sqrt{A}} \qquad (8)$$

where: E = Modulus of Elasticity
ν = Poisson's ratio
A = area of the plate or CBR plunger

Presuming that k_s is to be obtained from a plate load test, with the area of the plate and Poisson's ratio value as 20.268 cm^2 and 0.4 respectively the modulus of subgrade reaction, k_s for clayey sand soil can be computed as 123423.07 kN/m^3.

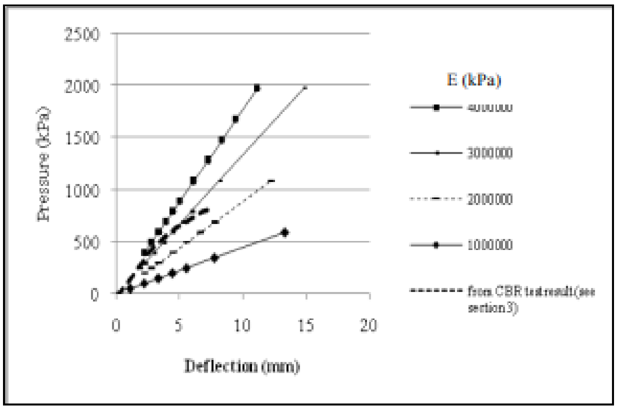


Figure 8. Pressure-Deflection results from FEM with various value of E (Pa)

The following is an estimate for the field plate load test based on the relative sizes of the CBR plunger and the field plate. However, this approach may be used with caution because it works for soil media whose behavior is linear elastic or nearly linear elastic. The correlation between the CBR and field plate load tests may be found by doing the following: a. It is shown that a semi- infinite elastic soil medium may support a rigid circular load.

$$(k_s)_{1i} = 1.13 \quad \frac{E}{(1-\nu^2)} \; \frac{1}{\sqrt{A_1}} \qquad (9)$$

where A_1 is the area of the CBR plunger.
For field plate load test of any size (usually of circular shaped plate size 760 mm diameter)

$$(k_s)_2 = 1.13 \quad \frac{E}{(1-\nu^2)} \; \frac{1}{\sqrt{A_2}} \qquad (10)$$

b. The ratio of CBR and plate load deflections from Equation (9) and Equation (10), is

$$\frac{(p/\delta)_{1i}}{(p/\delta)_2} = \frac{(k_s)_1}{(k_s)_2} = \sqrt{\frac{A_2}{A_1}} \; ; \; \sqrt{\frac{\pi\, r_2^2}{\pi\, r_1^2}} = \frac{r_2}{r_1} \qquad (11)$$

(for circular plate)

where,

A_1, r_1, δ_{1i} = for the area, radius and deflection of the CBR plunger.

A_2, r_2, δ_2 = for the area, radius and deflection of the plate from plate load test.

c. For the same value of p_1=p_2, we get from Equation (11)

$$\frac{\delta_2}{(\delta_1)_i} = \sqrt{\frac{A_2}{A_1}} = \frac{r_2}{r_1} \qquad (12)$$

The ratio of the field plate's radius to the CBR plunger's radius equals the correlation between these two deflections, which is expressed in Equation (12). d. On a medium of semi-infinite soil, the deflection of a CBR plunger can be approximated as follows. Calculate the value of for a given p from the CBR test result shown in Figure 4. Determine the soil's electrical conductivity (E) using the pressure (p) and load (P) values given in Figure 8 (P = p. area of the plunger)

Then, When considering the deflection of the CBR plunger on a semi-infinite elastic soil medium, it is important to remember that 1 = the deflection of the plunger in the CBR mould (load on constrained soil medium). The appendix details the procedures for predicting the outcomes of plate load tests with = 0, 0.3, and 0.4.

Additionally, it is worth noting that by reversing the aforementioned methods, CBR values may be anticipated from the plate load test results.

$$(k_s)_1 = 1.13 \quad \frac{E}{(1-\nu^2)} \; \frac{1}{\sqrt{A_1}} = \frac{(p_1)_i}{(\delta_1)_i} \qquad (13)$$

$(\delta_1)_i$, can be calculated, knowing p for the pressure and A, being the area of the CBR plunger (50.8 mm diameter) from the above Equation (13).

Hence, from the equation (12), the deflection for the field plate load test, $(\delta_2)_p$ can be predicted as,

$$\frac{(\delta_2)_p}{(\delta_1)_i} = \frac{r_2}{r_1} = \sqrt{\frac{A_2}{A_1}}$$

$$(\delta_2)_p = \frac{r_2}{r_1} \cdot (\delta_1)_i \qquad (14)$$

VII. CONCLUSION

The relationship between E and CBR has a number of benefits that can make it easier to get the modulus of subgrade reaction, ks, which is used to figure out how thick the pavement should be. b) The relationship between ks and CBR can be used to predict the results of field plate load tests and other elastic studies. (c) More logical ways of using E and design, like the threshold stress method (Shahu, 2000), can be made for real-world use.

This association will help improve the design of highway formations by using empirical factors like CBR value and analysis-based methods that use values of E or, threshold stress, liquefaction, etc. (d) The CBR test, which is easy to do in the lab with soil samples from the site that haven't been moved, can be used to predict how soils will behave at any depth. The modulus of subgrade response, ks, which is hard to figure out more than 1 or 2 m below Ground Level, can also be measured. (e) You can also figure out the CBR number from the data of the field plate load test by doing the steps in section 5 backwards. Appendix: Prediction of Plate Load Test (PLT) deflections from CBR test results Predict the PLT reaction for a plate with a diameter of 760 mm based on the results of a CBR test in which the area of the CBR pusher, AA1, was found to be 2026.8 mm2. Figure 2 shows the result of the

CBR test, which is used to predict how the PLT will work in the field. Poisson's ratio, vv = 0.4 iii. Poisson’s ratio, ***vv*** = 0 1. Find the deflection for the semi-infinite dirt material based on the result of the CBR test, (1)ii. Use the same steps with (i) and (ii), where the CBR number for Poisson's ratio is 4.5% and vv = 0. Then, the equation (13) can be used to figure out the displacement for the semi-infinite dirt medium from the CBR test, (1) ii. So, (1)ii equals 3.794 mm. 2. Then, Equation (15) is used to figure out what (2)pp will be. So, a CBR pusher on a semi-infinite elastic clay medium at a pressure of 400 kPa will bend by 3.43 mm, 3.63 mm, or 3.79 mm.

For a Poisson's ratio of 0.4, 0.3, and 0 respectively, the expected displacement of the field plate load test of a soil sample in the field will be 51.31 mm, 54.24 mm, and 56.77 mm. iv. The results of the above calculations for the pressure-deflection forecast of the field PLT. Figure 9 shows all of the pressure-deflection data from a single CBR test result (shown in Figure 4) for Poisson's ratio, vv, equal to 0, 0.3, and 0.4. This was done by following steps (i) through (iii).

1. Determination of the deflection for the semi infinite soil medium from the CBR test result, $(\delta_1)_i$.

At deflection, $\delta_1 = 2.5$ mm from the CBR test result in figure 2, the pressure, $p = 400$ kPa. Then from Figure 4, the value of modulus of elasticity for this soil, E is equal to 3900 kPa and by means of Figure 5 which has been developed a correlation of CBR vs. E, obtained the CBR value equal to 5.2%. With this E by means of Equation (14), the $(\delta_1)_i$ can been calculated. Hence, $(\delta_1)_i = 3.43$ mm.

2. Then to predict the value of $(\delta_2)_p$, the Equation (15) is used,

$$(\delta_2)_p = \frac{r_2}{r_1} \cdot (\delta_1)_i = \frac{380\ \text{mm}}{25.4\ \text{mm}} \cdot 3.43\ \text{mm} = 51.31\ \text{mm}$$

ii. Poisson’s ratio, $v = 0.3$

1. Determination of the deflection for the semi infinite soil medium from the CBR test result, $(\delta_1)_i$.

At deflection, $\delta_1 = 2.5$ mm from the CBR test result in figure 2, the pressure, $p = 400$ kPa. Then from Figure 5, the value of modulus of elasticity for this soil E is equal to 3900 kPa and by means of Figure 5, the CBR value equal to 4.7%. With this E, the $(\delta_1)_i$ can been calculated. Hence, $(\delta_1)_i = 3.6255$ mm.

2. Then to predict the value of $(\delta_2)_p$, the Equation (15) is used,

$$(\delta_2)_p = \frac{r_2}{r_1} \cdot (\delta_1)_i = \frac{380\ \text{mm}}{25.4\ \text{mm}} \cdot 3.6255\ \text{mm} = 54.24\ \text{mm}$$

$$(\delta_2)_p = \frac{r_2}{r_1} \cdot (\delta_1)_i = \frac{380\ \text{mm}}{25.4\ \text{mm}} \cdot 3.794\ \text{mm} = 56.77\ \text{mm}$$

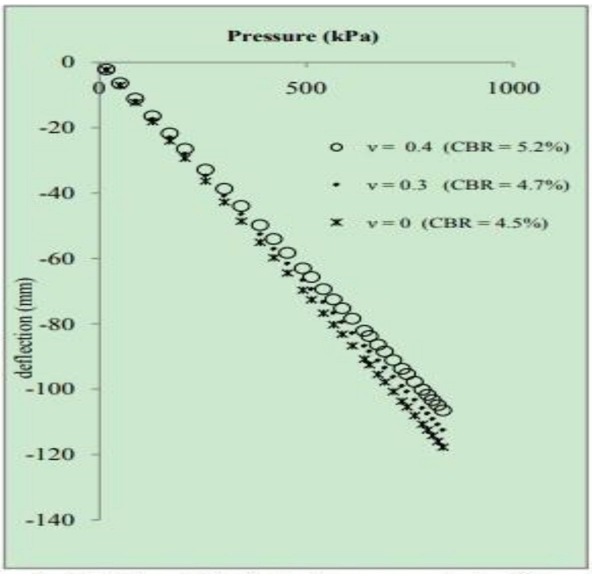


Figure 9. Prediction of field plate load test response for d = 760 mm (v = 0, v = 0.3, v = 0.4), E = 3900 kPa

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