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SUBGRADE STRENGTH/STIFFNESS EVALUATION

A WHITE PAPER
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Illinois Cooperative Highway and Transportation Research Program

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INTRODUCTION

Several tests/devices have been developed for evaluating subgrade strength/stiffness during construction. Some are intrusive (Vane Shear Tester or the Dynamic Cone Penetrometer) while others impart a light impulse load to the soil (Clegg Impact Soil Tester or the Light Drop Weight Tester).

The following methods are considered the most appropriate to evaluate the subgrade strength/stiffness during construction either because of demonstrated experience or because of previous promising results.

METHODS TO EVALUATE THE SUBGRADE STRENGTH/STIFFNESS

Several of the devices measure properties of the subgrade which have been correlated with CBR (California Bearing Ratio). IDOT has adopted the IBR (Illinois Bearing Ratio) instead of the CBR. In the IBR test the specimens are compacted using a static molding technique rather than a dynamic procedure using a compaction hammer as specified for the current CBR test (AASHTO T 193) (1). IDOT also has adopted the IBV (Immediate Bearing Value) which is a penetration test similar to that for the IBR, except that the test is conducted immediately after compacting the soil in a 100 mm (4 in.) mold without soaking (1). In this paper however, CBR has been used instead of IBR or IBV because the original equations were developed using that test and expressed as a function of CBR.

1. Vane Shear Test
   a. Description
      The vane shear test basically consists of forcing a vane equipped with four orthogonal blades into the soil and then rotating until the soil fails (Figure 1). The maximum torque value must be measured and recorded. The torsional force is then converted to a unit shearing resistance on the cylindrical failure surface.
The vane shear test is normally used for field testing, including tests carried out either on a wall or at the bottom of an excavation, but can also be performed in the laboratory on a confined specimen.

The vane shear test is generally used only for measuring the undrained shear strength of soft to stiff clays and normally as a preliminary investigation of these soft cohesive soils. The vane device should not be used for soils which drain or dilate during the test.

Field vane shear test procedures have been standardized in ASTM D2573 (Standard Test Method for Field Vane Shear Test in Cohesive Soil). These procedures recommend a four-bladed vane (Figure 2) with a height equal to twice the diameter of the vane. The above mentioned standard prescribes that the rotation must be carried out at a rate of 0.1-0.2 degrees/sec., that is 6-12 degrees/min.

![Figure 1.]

![Figure 2.]

Friction in the vane and instrument should be accounted for. Otherwise, the friction would be improperly recorded as soil strength. Friction under no-load conditions (such as a vane that allows a partial turn of free rotation prior to loading), must be determined. No side thrust in the measuring device, under peak load, should be permitted. Side thrust results in a change of frictional conditions (1).
b. Shear Strength

Following the recommendation of the ASTM D2573, vane height equal to twice the diameter, the soil shear strength can be calculated using the equation:

\[ S = \frac{T}{0.0021 \cdot D^3} \]  \hspace{1cm} (equation 1)

where:

\( S \) = Shear Strength (lb/ft²)

\( T \) = Torque (lb-ft)

\( D \) = Vane Diameter (in.)

Shear strength and CBR are related as follows:

\[ S = 2.25 \cdot CBR \]  \hspace{1cm} (equation 2)

\[ Q_u = 4.5 \cdot CBR \]  \hspace{1cm} (equation 3)

where:

\( S \) = Shear Strength / Cohesion (psi)

\( Q_u \) = Unconfined Compressive Strength (psi)

\( CBR \) = California Bearing Ratio

2. Clegg Impact Soil Test

a. Description

The Clegg Impact Soil Test provides a means for measuring soil strength. It is also used to confirm uniform compaction, identify poorly compacted areas and ineffective rolling of materials. The Clegg Impact Soil Test procedure has been standardized in ASTM D5874 (Standard Test Method for Determination of the Impact Value (IV) of a Soil).

The Tester consists of a compaction hammer operating within a vertical guide tube (Figure 3). The standard hammer is 4.5 kg (10 lb), 5 cm (1.97 in.) in diameter with a free fall of 45 cm (18 in.). When the hammer is released from a fixed height it falls through the tube and strikes the surface under test, decelerating at a rate determined by
the stiffness of the material within the region of impact. A precision accelerometer mounted on the hammer delivers its output to a hand held digital readout unit, which registers the deceleration in units of Impact Value (IV) which is a value expressed in units of tens of gravities (g) (i.e. IV = G/s/10). The IV indicates soil strength and shows good correlation with CBR test results.

![Figure 3.](image)

b. Correlation with CBR

The correlation recommended, based on results available from Australian, New Zealand and United Kingdom sources which cover a wide range of soils for both laboratory and in-situ conditions, is (2):

\[
CBR = \left[0.24 \cdot IV + 1\right]^2
\]

(equation 4)

where:

- CBR = California Bearing Ratio
- IV = Impact Value

This equation was obtained for the standard hammer, 4.5 kg (10 lb), 45 cm (18 inch.) drop, and 5 cm (1.97 inch.) diameter, and appears appropriate for general use. However, since CBR is particularly subject to high variability, even within one organization or one soil type, correlations from individual sources may vary from the
general equation. It should be noted that the data used to develop the correlation are for both samples at essentially the same density and moisture content and prepared in the same manner. Attempts have been made to correlate unsoaked IVs with soaked CBRs but with little success. Also the question of the effect of surcharge may need to be considered.

c. Clegg Hammer Modulus (CHM)

There has been increasing interest in using the Clegg Impact Soil Tester as a mean of arriving at a design elastic modulus for application in pavement design and analysis.

Conversion from IV to Clegg Hammer Modulus (CHM) can be made by applying theoretical concepts by which to produce relationships for the commonly used hammers.

The basic equations are as follows (3):

\[
\text{CHM} = 0.23 \cdot IV^2 \\
\quad \text{(20 kg, 30 cm drop, 13 cm diameter)} \quad \text{(equation 5)}
\]

\[
\text{CHM} = 0.088 \cdot IV^2 \\
\quad \text{(4.5 kg, 45 cm drop, 5 cm diameter, Standard Hammer)} \quad \text{(equation 6)}
\]

\[
\text{CHM} = 0.044 \cdot IV^2 \\
\quad \text{(2.25 kg, 45 cm drop, 5 cm diameter)} \quad \text{(equation 7)}
\]

\[
\text{CHM} = 0.015 \cdot IV^2 \\
\quad \text{(0.5 kg, 30 cm drop, 5 cm diameter)} \quad \text{(equation 8)}
\]

where:

CHM = Clegg Hammer Modulus (MPa)

IV = Impact Value

The coefficients in these equations have been derived using double integration of time versus deceleration to determine the deflection and using this in elastic plate
bearing theory to arrive at an elastic modulus. The use of CHM as a modulus for iterative analysis comparing calculated deflections with field observations should enable the coefficients to be refined from time to time.

On the other hand, Chowdhury & Nataatmadja (4) have proposed the following equation for the relationship between resilient modulus and the impact value when using the 20 kg (44 lb.) Clegg impact hammer:

\[ Mr = 88.4 \cdot IV \]  

(equation 9)

where:

- \( Mr \) = Resilient Modulus (MPa)
- \( IV \) = Impact Value (20 kg, 30 cm drop, 13 cm diameter)
  (44 lb, 12 in. drop, 5.12 in. diameter)

3. Light Falling Weight Deflectometer (LFWD) Test

a. Introduction

This test is performed to measure the stiffness modulus of the subgrade (or granular layers) which in turn, has been used widely, especially in Europe, for compliance testing for construction control. Traditionally, the measure of the stiffness modulus has been done using the static plate load bearing test, however, it is increasingly being replaced by the portable and quicker dynamic plate tests (5). A field test device will ideally be able to deal with the varied materials that could be found, and be sensitive enough to distinguish between their contrasting performance.

Frost et al. (6) cited that Fleming and Rogers considered in detail the requirements of tests to measure stiffness in-situ, identified impulse plate-loading devices, such as the falling weight deflectometer (FWD) type, as the most appropriate.

According to Fleming et al. (5) to replicate construction vehicle wheel loading, an in-situ test device should ideally measure the response of a transient load pulse of around 40 milliseconds or longer; loading applied through a bearing plate approaching 500 mm (19.7 in.) in diameter (to simulate a dual tire configuration); and a contact stress of around 200 KN/m² (29 lb/in²). However, since the required contact stress and load pulse duration needed to simulate vehicle loading on a layer at a given depth in a
partially completed pavement will vary due to the stress dependency of the materials used, some flexibility in the loading applied by a device is desirable.

Although the conventional FWD, as was already mentioned, is classified as an appropriate device, it is also sometimes considered unnecessarily sophisticated for subgrade and foundation testing; furthermore, it is not without limitations on weaker substrates in regard to both transducer range limits and portability (7). On the other hand, there are several portable dynamic test devices (LFWD) that measure in-situ elastic stiffness modulus for the material under test and that meet the above requirements. They exhibit many similarities in their mechanics of operation although there are many subtle differences in design and mode of operation, which lead to variations in the measured results.

These devices have a free-falling mass, guided during descent, which then impacts the bearing plate by way of a rubber buffer to provide a transient load pulse to the material under test. A protective casing on the bearing plate houses the transducer(s) that measure, in some manner, the deflection (and in some cases the transient force) to determine a stiffness modulus value (8). The stiffness (E) is determined using conventional static elastic theory, i.e., Boussinesq elastic half space as follows:

\[
E = \frac{K \cdot p \cdot r \cdot (1 - \nu^2)}{d} \quad \text{(equation 10)}
\]

where:

- \(E\) = Modulus
- \(K\) = 2 (if the plate is considered flexible), or \(\pi/2\) (if the plate is considered rigid)
- \(p\) = Applied Contact Pressure
- \(r\) = Plate Radius
- \(\nu\) = Poisson's Ratio
- \(d\) = Deflection

A brief description of the most common testing devices classified as LFWD follows.
b. Description of the most common LFWD

(1) Light Drop Weight Tester

The Light Drop Weight Tester is also known as German Dynamic Plate Bearing Tester (Figure 4) and it is described under this name in the German specifications.

This tester serves as an alternative to a static plate-bearing test in Germany. It comprises a total mass of 25 kg (55.1 lb), and a falling mass of 10 kg (22 lb) that drops 1 m (39.37 in.) and hits a spring-dashpot element producing a respective impact onto the 300 mm (11.8 in.) diameter bearing plate, within which is mounted a velocity transducer. The drop height of the falling mass is set such that the peak applied force is 7.07 kN (1589.4 lb), which implies 100 kPa (14.5 psi) contact stress, when calibrated on a standard (manufacturer's) foundation. The force is not measured during testing and the maximum deflection caused by the impact is calculated from the measured acceleration signal of the plate. The load pulse duration is 18±2 milliseconds. It can measure in the range 10-225 MN/m² (1450-32633 psi) (there are several manufacturers who claim slightly different ranges) (5).

The dynamic deformation modulus is defined according to the static deformation modulus (equation 10), whereby the whole device is tuned in a way that the mean contact pressure between plate and soil is approximately p=0.1 MN/m² (14.5 psi) independently of the soil stiffness. This dynamic deformation modulus does not describe the exact dynamic soil modulus because it does not take into account dynamic forces like forces of inertia and damping effects occurring during the testing process. The zone of influence of the test is reported as approximately one diameter in depth (8). The device is recommended for use on stiff cohesive soils, mixed soils and coarse-grained soils up to 53 mm (2.48 in.) in size (5).

The operational procedure recommended for this device (and adopted for the FWD) is six drops on the same spot to provide a single value of stiffness. The first three drops are termed precompaction, to remove any bedding errors, and are ignored. The deflections of the next three drops are recorded and displayed on the readout together with the computed average stiffness.
(2) TRL Foundation Tester

The Transport Research Laboratory Foundation Tester (TFT) (shown in Figure 5) comprises a manually raised 10 kg (22 lb) mass, which is released from a height controlled by the operator and falls onto a 300 mm (11.8 in.) diameter bearing plate via a rubber buffer. The total mass of the apparatus is 30 kg (66 lb). The load pulse duration is 15 to 25 milliseconds. The applied force and the deflection, inferred from a velocity transducer measuring through a hole in the bearing plate, are recorded automatically. The deflection derived for the material under test is determined by single integration of the velocity transducer signal to the point in time that the measured force reaches its peak. As a result, the actual peak deflection is not reported. It is stated that early trials have shown only 2% error.

It is currently a working prototype at the Transport Research Laboratory and is not commercially available. The operational procedure used for the TFT is the same as that used for the Light Drop Weight Tester. To match a target contact stress, more than one drop height has to be used normally, and an interpolation between
the result is needed. The analysis method for stiffness is for rigid plate and with a Poisson's ratio for granular soils of 0.3, and 0.45 for clays.

![Diagram of equipment setup](image)

**Figure 5. (8)**

(3) **Hand Held FWD Prima 100**

The Hand Held FWD Prime 100 (shown in Figure 6) is a device that has been recently developed and marketed, and is very similar to the TFT. It weighs 26 kg (57.3 lb) in total and has a 10 kg (22 lb) falling mass (although in the new version up to 20 kg (44 lb) drop weight is possible) which impacts a spring to produce a load pulse of 15-20 milliseconds. It has a load range of 1-15 kN (225-3372 lb), i.e. up to 200 kPa (29 psi) with its 300 mm (11.8 in.) diameter bearing plate (the new version also has the option of 100 (3.9 in.) and 200 mm (7.8 in.) diameter bearing plate). It measures both force and deflection, utilizing a velocity transducer with a maximum deflection of 2.2 mm (0.087 in.).

The standard device comes with the velocity transducer attached to the bearing plate, although it is possible to modify it to measure on the ground through a hole in the plate. It also has the capability of using a geophone beam for two extra
geophones enabling measurement with a total of three geophones (as seen in Figure 6).

The device currently requires a portable notebook computer for data output and analysis, and for stiffness analysis assumes a rigid plate and Poisson's ratio of 0.3 (which can be varied by the user).

![Figure 6.](image)

(4) Loadman

The Loadman (shown in Figure 7) is a light weight portable device for the measurement of deflections. The principle behind this device is to measure, with an accelerometer, the deflection caused by the load of a falling weight of 10 kg (22 lb).

The reported results are the maximum deflection, the modulus, the length of loading impulse, and the percentage of the rebound deflection compared with the maximum deflection, as well as the ratio of the modulus of the second measurement compared with the modulus of the first measurement. The apparatus consists of an aluminum tube of 132 mm (5.2 in.) diameter containing a free moving 10 kg (22 lb) weight. A circular plate of 132 mm (5.2 in.) (although it has the option of 200 (7.8 in.) and 300 mm (11.8 in.)) is attached to the base of the tube (the loading surface) with
controls, electronics, accelerometer, and weight support magnet positioned at the top.

The current methods of interpretation of Loadman testing results are based on the assumption that the modulus needed to cause the maximum measured deflection under a circular load can be found by relating the maximum deflection caused by a uniformly applied pressure to the elastic stresses as calculated by Boussinesq's theory in the underlying pavement and soil. For simplicity, Poisson's ratio is typically assumed to be 0.5 (9).

Technically, the device can be used on practically all kinds of construction sites to measure bearing capacity and for compaction control on bound, unbound and special layers as well as for laboratory tests of various kinds of materials.

![Figure 7](image)

**Figure 7.**

c. Field Evaluation of the LFWD

Several field and laboratory studies have been developed which have demonstrated some advantages and disadvantages in the use of the different devices described above, and normally they have been compared against the FWD. Among those studies is the work of Fleming et al. (5), Livneh et al. (7), Fleming (8) and a study by Gros cited in reference 8.
Fleming et al. (5) in recent research compared the following four different devices for measuring stiffness in-situ: Falling Weight Deflectometer, German Dynamic Plate Bearing Tester (GDP or Light Drop Weight Tester), TRL Foundation Tester, and Prima 100. They concluded that the devices all utilize simple static elastic theory to interpret an elastic stiffness modulus from measured (or assumed) values for contact stress and indirectly measured deflection. Dynamic effects are thus not taken into account. As the measurements are made only on the plate, or on the ground directly beneath the plate, the response of the underlying (interacting) layers is thus superimposed to produce a single surface deflection value. The stiffness is, therefore, usually termed the foundation, or composite, elastic stiffness modulus.

An important difference between the GDP and the other devices is the GDP measures the change in velocity (and by integration the deflection) of the bearing plate itself, as opposed to the material under test. This alone is not expected to cause the discrepancy frequently observed between the GDP results and the other devices. The GDP also assumes a contact stress, which is dependent on the stiffness of the material under the test, and this is thought to be a major source of error. The GDP signal processing (i.e. smoothing, digitizing and interpretation) may be responsible for the primary source of discrepancy, however.

The TFT also has a specific difference to the FWD and Prima 100 in that it calculates the stiffness using the peak force and the deflection at the point in time of the peak force. Thus, if a time lag exists between the peak force and the peak deflection then the TFT will underestimate the deflection and overestimate the actual stiffness.

Livneh et al. (7) compared the conventional FWD deformation moduli with their comparative LFWD (specifically the German Light Drop Weight Tester or GDP) deformation moduli by conducting in-situ comparative tests and concluded that the German Light Drop Weight Tester can serve as a cost-effective testing device for quality control and assurance during subgrade and capping-layer compaction. However, compared with conventional FWD moduli, the German Light Drop Weight Tester moduli are of a smaller magnitude: 0.3 to 0.4 times the conventional FWD moduli in their study and 0.5 to 0.6 times these moduli in other studies. They recommend that the
discrepancy in moduli results requires the use of the most critical values in order to obtain the proper safety-factor.

Fleming (8) compared the following three portable devices: German Dynamic Plate Bearing Tester (called also GDP or Light Drop Weight Tester), TRL Foundation Tester, and Prima 100, and the FWD was used as the benchmark. He concluded that field investigations showed that the devices gave contrasting results on the same test constructions, and are influenced by many test-related factors and site-specific material factors. The portable devices appear to apply sufficiently long transient loading pulse duration to lessen the dynamic inertia effects, though further work is required to estimate the error from using the conventional static analysis method for stiffness modulus.

The dynamic plate devices all assume that the maximum deflection is elastic, even though the velocity transducers are interpreted from the loading, and not unloading, cycle and will therefore include any permanent deformation incurred.

When the construction-related and natural material variability on site is taken into account, plus weather effects, and the effect of the interaction of the different layers (with different stress dependent properties) it is evident that predicting field stiffness or setting suitable targets for compliance is a significant challenge. However, it is believed that the measurement of stiffness in-situ during construction can only improve current controls and lead to an increased understanding of the field behavior of the materials being utilized. It is considered that the true stiffness may be an impractical goal for fieldwork, and that a potentially simpler but repeatable measure may satisfy construction-monitoring requirements.

In addition, the findings suggest that the ideal portable test device should comprise both a force and deflection transducer, have a suitable low mass bearing plate and low stiffness damper.

Fleming also concluded that of the three portable devices reviewed it is evident that Prima 100 is the most promising. It has many good design features, measures both force and deflection and correlates well with the FWD (from limited data only).

Newcomb et al. (9) presented the results of a detailed field study performed by Gros to compare the Loadman, the FWD, and the plate-loading test. The findings
indicate that for the subgrade soils, the results obtained from the Loadman correlated reasonably well with those obtained from the FWD, as was the case between the Loadman and the plate-loading test. Furthermore, the results showed that the Loadman modulus values were always lower than those of the FWD or the plate-loading test. In summary, Gros concluded that the modulus values obtained by the Loadman are almost equal to the plate-loading test values and equal, except for a shift, to FWD values. However, the Loadman is still a relatively new test with a limited database of experience. Improvements in the theory behind the test may also lead to better predictions. The introduction of layered materials, rather than the homogeneous half-space represented by Boussinesq’s theory and the allowance for Poisson’s ratios different from 0.5, may significantly improve the Loadman predictions.

4. Soil Stiffness Gauge (SSG) Test

a. Introduction

This test is performed to measure the in-place stiffness of compacted soils. The stiffness is defined as the ratio of the force applied on a boundary through a loading area divided by the displacement experienced by the loaded area. It has units of force per unit length. The loaded area is typically a plate which can be square or circular or in the shape of a ring.

b. Description of the SSG

The Soil Stiffness Gauge (GeoGauge or Humbold Stiffness Gauge (HSG)) is a recently developed nondestructive testing device that measures the in-place stiffness of compacted soils at a rate of about one test per minute (Figure 8.). The SSG weighs about 10 kg (22 lb) is 28 cm (11 in.) in diameter, 25.4 cm (10 in.) tall and rests on the soil surface via a ring-shaped foot.

The SSG measures the impedance at the surface of the soil. In other words, it measures the stress imparted to the surface and the resulting surface velocity as a function of time. Stiffness, force over deflection, follows directly from the impedance. The SSG imparts very small displacements to the soil (<0.00127 mm (0.00005 in.)) at
25 steady state frequencies between 100 and 196 Hz. The stiffness is determined at each frequency and the average is displayed.

The theoretical basis for the SSG is that the stiffness of soil can be expressed as the ratio of applied force to measured displacement, i.e., $K = P/\Delta$. The SSG can be viewed as the dynamic equivalent to the plate-loading test, with the exception that the induced strains in the soil are smaller. In both cases, a force $P$ is applied to the soil by means of a plate or ring. The soil deflects an amount, $\Delta$, which is proportional to the foot geometry, the modulus, and Poisson’s ratio of the soil. In plate-loading tests, large forces are necessary to produce adequate deflection to measure. On the other hand, the SSG uses technology borrowed from the defense industry to measure very small deflections, allowing much smaller loads, but also restricting the range of loads and induce strains to the lower end of the spectrum. Rather than measuring the deflection resulting from the SSG weight directly, it is vibrated, producing small changes in $P$ that produce small deflections. To filter out the deflections resulting from equipment operating nearby, the SSG is used over a range of frequencies.

Figure 8.

Currently, the SSG is still in a developmental stage and being tested and evaluated. IDOT is participating in the SSG FHWA Pooled Fund Study. It is contended that the SSG is a promising alternative to the nuclear density gauge for evaluating the compaction of constructed embankments. A potential disadvantage with the SSG is the low strain level at which the soil is tested. Its current design was geared specifically to
measuring a range of modulus and the stiffness of the top 10 to 20 cm (4 to 8 in.) of a wide range of soils. This test would be significantly enhanced if a correlation was established between the measured low-strain moduli and those associated with actual loading conditions at higher strain levels (9).

5. Corp of Engineers Cone Penetrometer (CECP) Test
a. Description

The Corp of Engineers Cone Penetrometer (CECP) (Figure 9) or Static Cone Penetrometer was developed by the Corps of Engineers (10) for use in trafficability studies. It can be used to determine the in-situ strength. The CECP can also be used during the field investigation, for preliminary estimation of subgrade treatment. It is lighter, and less difficult to use than the Dynamic Cone Penetrometer.

The CECP consists of a 30-degree cone, with a 0.5 in.\(^2\) (3.23 cm\(^2\)) base area, a 18 to 40 in. (45.7 to 101.6 cm) long, graduated steel rod, 5/8 in. (1.6 cm) diameter, and a proving ring or spring-calibrated dial gauge for measuring the cone index (CI) (10).

![Figure 9.](image)

The CECP test is conducted by pushing the cone slowly into the soil by hand for field application or may be machine mounted for laboratory use. The penetration is sustained at a constant rate, approximately 72 in./min (1.8 m/min). The CI is obtained by dividing the penetrometer load by the projected base area of the cone. The units of the CI are psi, but they are not listed in practice. In most cases, CI is determined for
various depths of soil penetration. Normally, the proving ring has a capacity of 150 lb (667 N), which implies that the CECF is limited to a CI of 300.

b. Correlation with CBR

CBR can be estimated using equation 11:

\[ CBR = \frac{CI}{40} \]  

(equation 11)

where:
CBR = California Bearing Ratio
CI = Cone Index (psi)

The Corps of Engineers also has developed a procedure for considering the remolding effects noted for many fine grained soils. The test consists of measuring the CI of a soil sample confined in a small cylinder (2 in. (5 cm) in diameter by 8 in. (20 cm)), before and after pounding it with 100 blows of a 2.5 lb (1.13 kg) tamper falling 12 in. (30.5 cm). The Remolding Index (RI) is obtained by dividing the remolded (after pounding it) CI by the CI before pounding it. A Rating Cone Index (RCI), the final measure of a soil trafficability, is obtained as follows:

\[ RCI = CI \cdot RI \]  

(equation 12)

where:
RCI = Rating Cone Index (psi)
CI = Cone Index (psi)
RI = Remolding Index

Table 1 shows mean values for Cone Index (CI) representative for different types of soils in a wet season condition.
Table 1.

<table>
<thead>
<tr>
<th>USCS Type</th>
<th>Mean CI</th>
<th>USDA Type</th>
<th>Mean CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP - SM</td>
<td>194</td>
<td>LS</td>
<td>188</td>
</tr>
<tr>
<td>SC</td>
<td>175</td>
<td>S</td>
<td>184</td>
</tr>
<tr>
<td>SM - SC</td>
<td>172</td>
<td>SCL</td>
<td>180</td>
</tr>
<tr>
<td>SM</td>
<td>150</td>
<td>SL</td>
<td>159</td>
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<td>Si</td>
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<tr>
<td>PI</td>
<td>63</td>
<td>PI</td>
<td>63</td>
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</tbody>
</table>

6. Dynamic Cone Penetrometer (DCP) Test

a. Description

The Dynamic Cone Penetrometer (DCP) (Figure 10) was developed in Australia (Victoria Country Roads Board) by A. J. Scala in the mid 1950’s (11), and has been used extensively in many countries because it is a simple, rugged and economical in-situ pavement evaluation test.

The DCP test measures the penetration resistance, in terms of inches per blow (millimeters per blow), while the cone of the device is being driven into the pavement structure or the subgrade. It is normally used to check the subgrade stability and depth of subgrade treatment during construction.

The DCP is portable and uses a 60-degree cone, with a 315 mm² (0.5 in.²) base area attached to a rod. The mass of the hammer is typically 8 kg (17.6 lb), and the drop height is 575 mm (22.6 in.), yielding a theoretical driving energy of 45 J (or 14.3 J/cm²).

The test is conducted by driving the cone into the soil, by dropping the hammer on the drive anvil from the drop height specified, and measuring the amount of penetration per blow. This penetration is a function of the in-situ shear strength of the material. The profile in depth therefore, gives an indication of the in-situ properties of the materials up to the depth of penetration, which is 45 to 90 cm (18 to 36 in.), as needed.
b. Correlation with CBR

Several researches have developed good correlations between DCP measurements and the California Bearing Ratio (CBR). Examples include research by Kleyn (1975), Harison (1987), Livneh (1987), McElvaney and Bunadi-Djatrika (1991), Livneh et al. (1992), Webster et al. (1992), Livneh and Livneh (1994), Webster et al. (1994), Ese et al. (1994), Coonse (1999), and Gabr et al. (2000) (12, 13). Many of the relationships between DCP and CBR have converged to the following form (12):

\[ \log(CBR) = a + b \cdot \log(PR) \]  

(equation 13)

where:

- CBR = California Bearing Ratio
- PR = DCP penetration rate (normally in mm/blow)
- \(a\) = constant that ranges from 2.44 to 3.54 (when mm/blow is used)
- \(b\) = constant that ranges from -1.0 to -2.0 (when mm/blow is used)
Table 2 is a summary of the most common correlations.

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Correlation equation</th>
<th>Number of data points</th>
<th>Field or laboratory based study</th>
<th>Material tested</th>
<th>Year of work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livneh (12)</td>
<td>( \log(CBR) = 2.56 - 1.16 \log(DCP) )</td>
<td>76</td>
<td>Laboratory</td>
<td>Granular and cohesive</td>
<td>1991</td>
</tr>
<tr>
<td>Livneh et al. (12)</td>
<td>( \log(CBR) = 2.45 - 1.12 \log(DCP) )</td>
<td>135</td>
<td>Field and lab.</td>
<td>Granular and cohesive</td>
<td>1993</td>
</tr>
<tr>
<td>Harrison (12)</td>
<td>( \log(CBR) = 2.55 - 1.14 \log(DCP) )</td>
<td>72</td>
<td>Laboratory</td>
<td>Granular and cohesive</td>
<td>1987</td>
</tr>
<tr>
<td>Smith and Pratt (12)</td>
<td>( \log(CBR) = 2.56 - 1.16 \log(DCP) )</td>
<td>Unknown</td>
<td>Field</td>
<td>Unknown</td>
<td>1983</td>
</tr>
<tr>
<td>Keyn (12,14)</td>
<td>( \log(CBR) = 2.61 - 1.26 \log(DCP) )</td>
<td>2,000</td>
<td>Laboratory</td>
<td>Unknown</td>
<td>1975</td>
</tr>
<tr>
<td>NCDO (12)</td>
<td>( \log(CBR) = 2.60 - 1.07 \log(DCP) )</td>
<td>Unknown</td>
<td>Adaptation &amp; field and lab.</td>
<td>ABC 2) and cohesive</td>
<td>1998</td>
</tr>
<tr>
<td>Norwegian, Rosic Research (Ese et al.) (12)</td>
<td>( \log(CBR) = 2.44 - 1.07 \log(DCP) )</td>
<td>79</td>
<td>Field and lab.</td>
<td>ABC</td>
<td>1995</td>
</tr>
<tr>
<td>Course (12)</td>
<td>( \log(CBR) = 2.53 - 1.14 \log(DCP) )</td>
<td>15</td>
<td>Laboratory</td>
<td>Piedmont residual soil</td>
<td>1989</td>
</tr>
<tr>
<td>Webster et al. (13)</td>
<td>( \log(CBR) = 2.46 - 1.12 \log(DCP) )</td>
<td>116</td>
<td>Field</td>
<td>Different soil types</td>
<td>1992</td>
</tr>
<tr>
<td>Webster et al. (9)</td>
<td>( \log(CBR) = 2.54 - 1.00 \log(DCP) )</td>
<td>Unknown</td>
<td>Field</td>
<td>CH material</td>
<td>1994</td>
</tr>
<tr>
<td>Webster et al. (9)</td>
<td>( \log(CBR) = 3.54 - 2.00 \log(DCP) )</td>
<td>Unknown</td>
<td>Field</td>
<td>CL material, CBR&lt;10%</td>
<td>1994</td>
</tr>
</tbody>
</table>

Note:  
1) The researcher's name is as appears in the reference which is in parentheses.  
2) DCP: Penetration rate (mm/blow).  
3) ABC: Aggregate Base Course.  

Each correlation depends on the type of material used, the number of data collected, and if the relationship is based on a field or a laboratory study. On the other hand, the natural variability of the material also contributes to the difference among the different correlations. However, it has to be noted that the researchers do not mention the standard followed for the CBR test.
Figure 11 shows the plot of six different and representative correlations of Table 2. As can be seen, Kleyn (1975) (also known as the South African correlation), Webster (1992) (also known as the Corp of Engineers correlation), and Ese (1995) (based on a Norwegian road research) are very similar at PR values below 20 mm/blow (e.g. for 4 mm/blow each one gives a CBR of 71.7, 61.1, and 62.5 respectively, and for 100 mm/blow each one gives a CBR of 1.2, 1.7, and 2.0 respectively). The equation corresponding to North Carolina Department of Transportation (NCDOT) (12) is somewhat different from the three already mentioned, but the number of data points used to obtain the correlation is unknown. If this correlation is compared with Webster (1992), it can be seen that for 4 mm/blow, the CBR will be 90.3 and 61.1 respectively, and for 100 mm/blow, the CBR will be 2.9 and 1.7 respectively.

On the other hand, Webster (1992) is based on a data base of field CBR versus DCP penetration rate values collected by the Water Experiment Station, for many sites and different soil types. In addition, correlation test results by Harison (1987), Kleyn (1975), Livneh and Ishai (1987), and Van Vuuren (1989) were compared with the data base test values, and then the Webster (1992) equation was selected as the best correlation (13).

Newcomb et al. (9) indicate that in 1994, Webster et al. updated the equation of 1992 for heavy (CH) and lean (CL) clays, resulting in the two new equations shown in Figure 11. The large difference between the CH/CL equations and the Webster (1992) equation (the CH relation is not conservative) is of concern.

The Kleyn/South African and Webster (1992) equations for estimating CBR from DCP data are similar. For PRs>20 mm/blow, the Kleyn equation is conservative (compared to Webster (1992)).

IDOT currently uses the Kleyn equation. It is recommended to continue to use this equation.
7. Dual Mass Dynamic Cone Penetrometer (DMDCP) Test

a. Description

The Dual Mass Dynamic Cone Penetrometer test (DMDCP) (Figure 12) was developed by the US Army Corps of Engineers and is basically the same as the traditional DCP described above (60-degree cone, with a 315 mm² (0.5 in.²) base area attached to a rod and a drop height of 575 mm (22.6 in.).

During the test, the DMDCP is driven into the soil by dropping either a 8 kg (17.6 lb) (when working as the DCP described in 6 above) or a 4.6 kg (10.1 lb) sliding hammer from the standard drop height of 575 mm (22.6 in.). The 8-kg (17.6-lb) hammer is converted to 4.6-kg (10.1-lb) by removing the hexagonal set screw and removing the outer steel sleeve as shown in Figure 13.
The cone penetration caused by one blow of the 8-kg (17.6-lb) hammer is essentially twice that caused by one blow of the 4.6-kg (10.1-lb) hammer (13). The 4.6-kg (10.1-lb) hammer is more suitable for use and yields better test results in weaker soils having CBR values of 10 or less. The 8-kg (17.6-lb) hammer penetrates high strength soils quicker and may be preferred when these type of soils are encountered. However, the 4.6-kg (10.1-lb) hammer can be used on soils up to CBR 30.

Figure 12.

The depth of cone penetration is measured at selected penetration or hammer drop intervals and the soil shear strength is reported in terms of DCP penetration rate (PR). The PR is based on the average penetration depth resulting from one blow of the 8-kg (17.6-lb) hammer. Thus, the average penetration per hammer blow of the 4.6-kg (10.1-lb) hammer must be multiplied by 2 in order to obtain the DCP penetration rate (which is based on the 8-kg (17.6-lb) hammer) (13).

Figure 13.
8. Automated Dynamic Cone Penetrometer (ADCP) Test

a. Description

In recent years the Automated Dynamic Cone Penetrometer (ADCP) with data acquisition system incorporated (Figure 14) has been developed. The ADCP performs the same measurements as the portable standard DCP (as described in 6), because it maintains the same weight, hammer falling and characteristics of the cone. However, the system improves the accuracy and repeatability of the test through the use of an automated drop hammer and data collection system. At this time, the correlation data between the manual and the automated DCP is limited.

Fully automated, the test process includes mechanical lift and release of the drop hammer, measurement and recording of the penetration on each drop, extraction of the penetrometer rod from the soil at the conclusion of the test, and automated processing of the test data to provide an easy-to-read report of the test. The user can view the test results versus depth, convert data to CBR, plot CBR versus depth, and define layer interfaces and compute the average properties for each layer. In addition, several data sets may be viewed simultaneously.

The equipment is also capable of communicating with recording data from a soil moisture resistivity probe, allowing to collect data of moisture, resistivity, and temperature of the soil being tested.

Figure 14.
9. Correlation Charts for Estimating CBR

Figure 15 shows the correlation charts for estimating CBR from DCP penetration rate, CI and $Q_0$. 

![Figure 15](image-url)
REFERENCES

10. Ayers, M. E., "Rapid Shear Strength Evaluation of In Situ Granular Materials Utilizing The Dynamic Cone Penetrometer," Thesis For The Degree of Doctor of Philosophy in Civil Engineering, University of Illinois at Urbana-Champaign, 1990.


**WEBITES**

1. Company: Dr Baden Clegg Pty Ltd
   Topyc: Clegg Impact Soil Tester
   Website: [www.clegg.com.au](http://www.clegg.com.au)

2. Company: Carl Bro Pavement Consultants
   Topyc: Hand Held FWD Prima 100
   Website: [www.pavement-consultants.com](http://www.pavement-consultants.com)

3. Company: Gerhard Zorn Mechanische Werkstaten
   Topyc: Light Drop Weight Tester
   Website: [www.zorn-online.de](http://www.zorn-online.de)

4. Company: AL-Engineering Oy
   Topyc: Loadman
   Website: [www.al-engineering.fi](http://www.al-engineering.fi)

5. Company: Humboldt
   Topyc: Soil Stiffness Gauge
   Website: [www.hmc-hsi.com](http://www.hmc-hsi.com)

6. Company: Vertek
   Topyc: Automated Dynamic Cone Penetrometer
   Website: [www.vertek.ara.com](http://www.vertek.ara.com)