Laboratory Correlation Study of Near-Surface Response Parameters

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A laboratory study was performed to investigate the correlations between the Clegg Impact Value (CIV), California Bearing Ratio (CBR), and Cone Index (CI). CIV values were obtained using a Clegg Impact Soil Tester. A prototype automated cone penetrometer (30° right circular cone with base diameter of ⅝ in.) was used to develop CI data. The correlation data were obtained using soil specimens constructed in a 19.25-in.-diameter by 22-in.-deep laboratory compaction mold. Three levels of soil type, moisture content, and compactive effort were used to develop soils with a range of CBR from approximately 1 to 30. Satisfactory simple linear correlation (adjusted R^2 values ranged from 0.94 to 0.98) were developed between CIV values and the square root of CBR. Correlations between CIV and CBR were less satisfactory with adjusted R^2 values between 0.63 and 0.75. Useful correlations (adjusted R^2 values ranged from 0.58 to 0.82) were also developed between the CI values at 2 and 6 in. of penetration depth and CIV. All statistical relationships were significant at an alpha level of 0.0005.

Advances in digital electronics and instrumentation technology have created a developmental opportunity for innovative soil and pavement materials testing equipment. Improved cost-effective field measurements amenable to statistically based quality assurance programs continue to be an applied research priority. Consequently, new equipment incorporating state-of-the-art electronics for near-surface data acquisition and analysis has become commercially available.

One recently developed dynamic response device for soil and pavement materials evaluation is the Clegg Impact Soil Tester. Described as a "soil compaction tester," (*1*) the instrument resembles a laboratory compaction hammer. A 10 lb weight free-falls through a PVC plastic guide tube. The height of vertical drop is 18 in. An accelerometer measures the deceleration of the weight as it impacts and penetrates the soil surface. The maximum deceleration, measured in gravitational units, is multiplied by 10 and digitally displayed. This value is referred to as "Impact Value" or "Clegg Impact Value." Extensive research conducted in Australia (*2–4*) by Clegg, the inventor of the instrument, has suggested that useful correlations exist between the Clegg Impact Value (CIV) and California Bearing Ratio (CBR), elastic modulus, and percent compaction. In effect, the CIV value evaluates the stiffness of the surface being impacted.

An experimental laboratory research program was designed to further evaluate the statistical correlations between CIV and CBR. In addition, Cone Index Values (CI) developed using a prototype automated cone penetrometer, developed by Khedr et al. (*5*) were also obtained for new correlations with the Clegg Impact Soil Tester.

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EXPERIMENT DESIGN

The laboratory testing program was designed to generate sufficient data for a study of the correlations among CIV, CBR and CI. Three soil types, 3 compaction water contents, and 3 compactive efforts were used to develop 27 treatment combinations for the correlation study.

The soil types were a low plasticity clayey sand [SP-SC by the Unified Soil Classification System (USCS), A-2-4 by AASHTO], a gravelly silty sand (SM by USCS, A-1-b by AASHTO), and a highly plastic inorganic clay (CH by USCS; A-7-6, GI = 34 by AASHTO). Different compactive efforts were achieved by using three different sizes of plates as base-mounted feet on an air-pressure operated vibratory hammer. Low compactive effort used a 9-in.-diameter plate and 2 coverages per compactive lift. High compactive effort used a 5.2-in.-diameter plate and 6 coverages per lift. Compaction moisture contents were based on the standard proctor compaction test. Nominal water contents were minus 2 percent of optimum and plus 2 percent of optimum moisture content. The combination of factors produced a satisfactory range of CBR values generally less than 30.

In order to prepare compacted specimens for testing, a cylindrical mold (19.25-in. diameter and 22-in. depth) was designed and fabricated. The compaction process was based on a procedure reported by Moore and Haliburton (*6*) used to prepare large laboratory soil samples for the calibration of nuclear moisture-density equipment. Each test was prepared using a selected soil type, a predetermined moisture content, and an estimated amount of dry soil based on target values of compacted dry unit weight. After uniformly combining the pulverized dry soil and water, the mixture was placed in the mold for four compacted lifts using one of three levels of compactive efforts. Each lift was approximately 4 in. thick after compaction.

TEST PROCEDURES

Clegg Impact Soil Tester

The Clegg Impact Soil Tester was the focus of the correlation study. Two CIV values were studied. The instrument instructions stipulate that the hammer be dropped four times to determine the CIV values for a test location. The instrumentation measured the decleration for each drop, but only the maximum value is stored and used as the output value after the four drops. This value will be called CIVHI. However, the research was conducted by recording the individual CIV values for each drop at each location on the compacted soil specimen. The average of the first four drops (CIV4) was also used as correlates. This average was used to determine if better correlations could be developed than by using CIVHI and if the penetration of hammer in successive drops was an important influence given that soil densification and deformation takes place.

Each CIV value shown in the correlation represents the average value of three tests taken within 6 in. of each other. The CIV value does not represent a fundamental soil property, but is a measurement of dynamic soil response. It appears probable that the precision of the CIV parameter is limited, and reliance on a single value at a given test location is imprudent. Operation of the equipment is simple, and the use of three observations will not burden field personnel. From a statistical standpoint, the use of means reduces the inherent variation in the correlate.

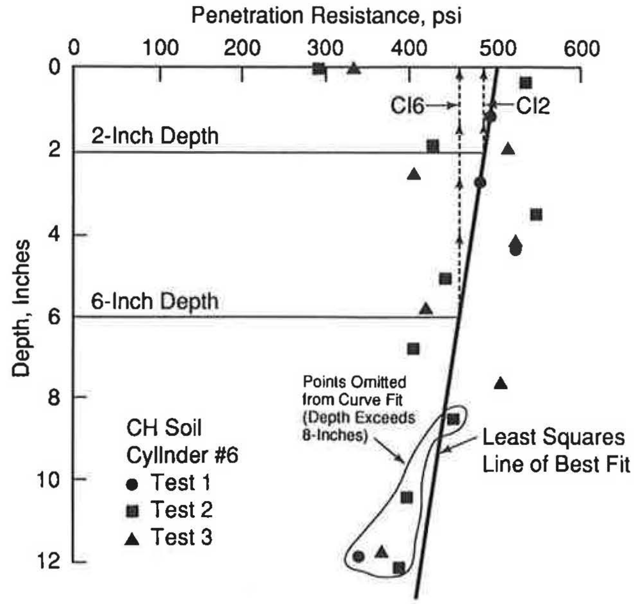

FIGURE 1 Cone Index estimation.

California Bearing Ratio

A conventional, manually operated test set-up mounted in a steel frame was used for the CBR laboratory test. The basic vertical deformation data were obtained with a dial gauge, and the soil penetration resistance was monitored using proving ring deformations. The CBR data are also the average of three tests taken within 6 in. of each other on the surface of the compacted specimens. A 10 lb surcharge was used in each CBR test.

Automated Cone Penetrometer

The automated cone penetrometer used a 30° right circular cone with a base diameter of ⅝ in. As the cone penetrates the soil, a recorder prints the penetration resistance in pounds along with the penetrometer depth in inches. The CI is the tip penetration resistance divided by the cone base area (psi).

The CI values used in the correlations are not averages. Three penetrometer tests were conducted on each compacted specimen. The data from all three tests were conducted on each compacted specimen. The data from all three tests were plotted as shown in Figure 1. A simple linear regression was placed through the plot of cone penetration resistance and penetration depth using data to a depth of 8 in. Cone penetration resistance was estimated using this regression at depths of 2 in. (CI2) and 6 in. (CI6).

STATISTICAL CONSIDERATIONS

The significance level of the sample Pearson correlation coefficient for all regressions shown in this paper is less than 0.0005 (Type I error in rejecting the hypothesis that the population correlation coefficient between the correlates is zero). An "adjusted R^2" coefficient is reported because the square of Pearson's correlation coefficient is usually an overly optimistic estimate of how well the linear model based on the sample actually fits the population (*7*). The R_a^2 statistic for a simple linear regression is defined as

$$R_a^2 = R^2 - [(1 - R^2)/(N - 1)]$$

where N is the number of data pairs and R is the Pearson correlation coefficient.

DISCUSSION OF RESULTS

Table 1 presents a summary of the correlation and regression results for 14 cases. Detailed data summaries and other correlations between the automated cone penetrometer and CBR can be obtained elsewhere (*8*).

The statistical results for the individual soils are given for the square root curve fits to illustrate the similarity. Clegg (*3*) published a model using Australian soils that is quite similar $[(\text{CBR})^{1/2} = 0.26\text{CIVHI}]$. The combined soils data plots are given in Figures 2 and 3 for the square root models. The adjusted R^2 value and standard error are slightly better using the average of four drops instead of CIVHI. Although the practical significance of this difference may be trivial, the instrumentation could be easily modified to display both the CIVHI and CIV4 if this trend proves to be important as experience increases using the instrument for quality control.

Figures 4 and 5 illustrate the simple linear regression between CBR and the Clegg output values using the combined data sets. These illustrate the variation associated with the CBR data for a given Clegg Impact Value. A comparison of the plots clearly demonstrates that the quantitative effect of averaging is a reduction in CIV parameter by one or two units.

TABLE 1 CORRELATION AND REGRESSION SUMMARY

Regression	Adjusted R^2	Standard Error	Data Set
Sqr (CBR) = 0.20 (CIVHI)	0.94	0.58	SP-SC Soil n=11
Sqr (CBR) = 0.27 (CIVHI)	0.98	0.40	SM Soil n=9
Sqr (CBR) = 0.30 (CIVHI)	0.98	0.58	CH Soil n=9
Sqr (CBR) = 0.25 (CIVHI) Figure 2	0.94	0.70	All Soils n=29
Sqr (CBR) = 0.27 (CIV4)	0.96	0.46	SP-SC Soil n=11
Sqr (CBR) = 0.33 (CIV4)	0.97	0.53	SM Soil n=9
Sqr (CBR) = 0.36 (CIV4)	0.95	0.67	CH Soil n=9
Sqr (CBR) = 0.32 (CIV4) Figure 3	0.95	0.63	All Soils n=29
CBR = -4.40 + 1.23 (CIVHI) Figure 4	0.63	4.21	All Soils n=29
CBR = -4.71 + 1.61 (CIV4) Figure 5	0.75	3.48	All Soils n=29
CI2 = 45.19 (CIVHI) Figure 6	0.82	235.08 psi	All Soils n=29
CI2 = -188.48 + 77.48 (CIV4) Figure 7	0.68	202.95 psi	All Soils n=29
CI6 = 59.21 (CIVHI) Figure 8	0.70	428.55 psi	All Soils n=30
CI6 = -384.45 + 116.16 (CIV4) Figure 9	0.58	374.07 psi	All Soils n=30

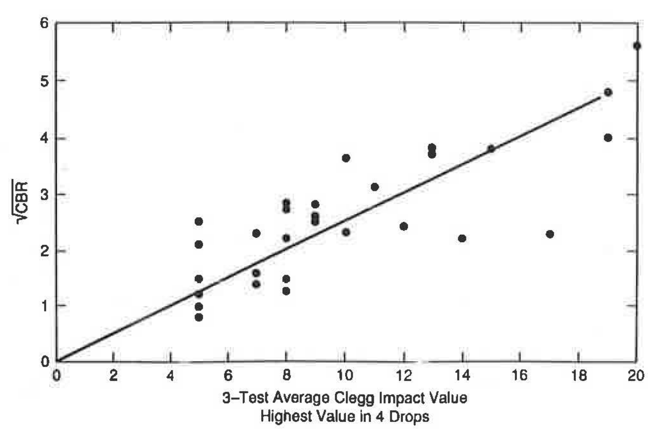

FIGURE 2 (CBR)$^{1/2}$-CIVHI regression (all soils).

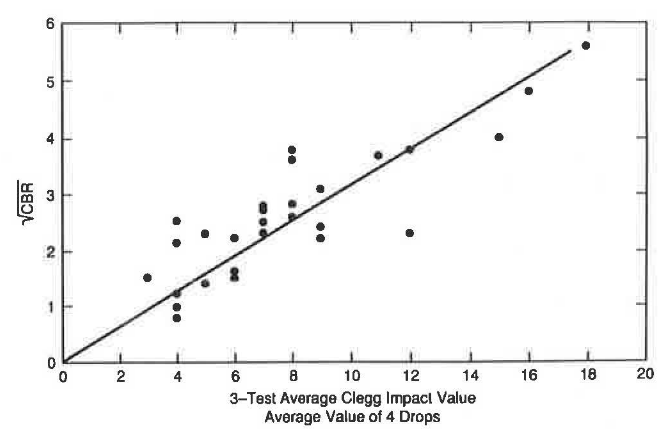

FIGURE 3 (CBR)$^{1/2}$-CIV4 regression (all soils).

Figures 6–9 illustrate the relationship between CI2, CI6, and the Clegg parameters. Two lines are shown in Figures 6 and 8. In these cases, the intercept of the regression (shown by the solid line) was not statistically significant at an alpha level of 5 percent. Therefore, the regressions given in Table 1 represent the dashed lines in Figures 6 and 8. These relationships were developed by forcing the regression through the origin.

The cone penetrometer relationships using CIVHI have higher adjusted R^2 values but larger standard errors than the regressions using the average of four drops. Because these relationships appear to be the first reported in the technical

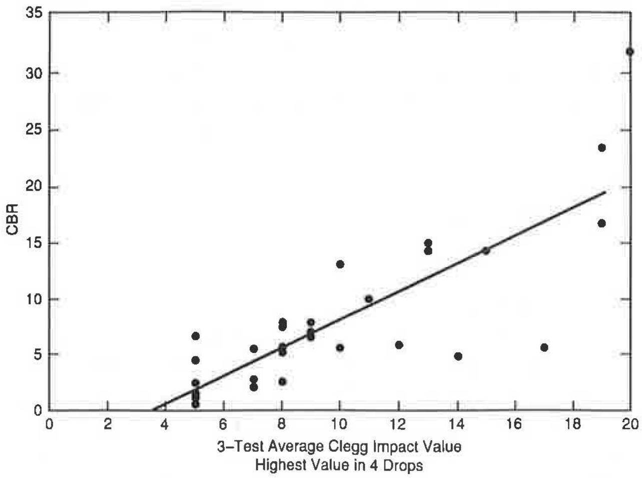

FIGURE 4 CBR-CIVHI regression (all soils).

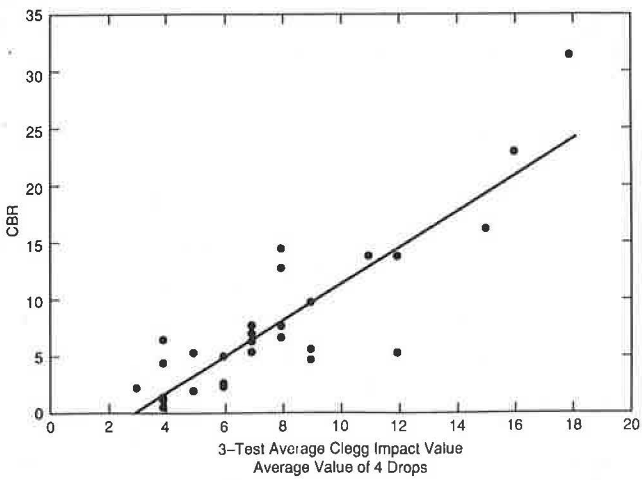

FIGURE 5 CBR-CIV4 regression (all soils).

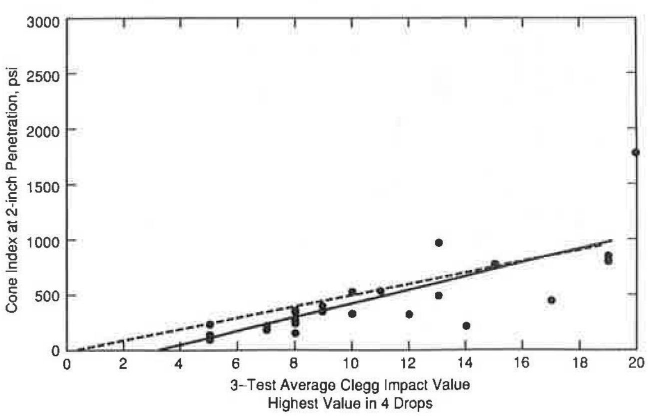

FIGURE 6 CI2-CIVHI regression (all soils).

literature, no comparisons with previous work are possible. However, research with the automated cone penetrometer suggests that the confidence levels, and hence the standard error, about estimated cone index values may be useful.

Two cone index values were studied to determine if the effect of depth on the sensitivity of the Clegg instrument could

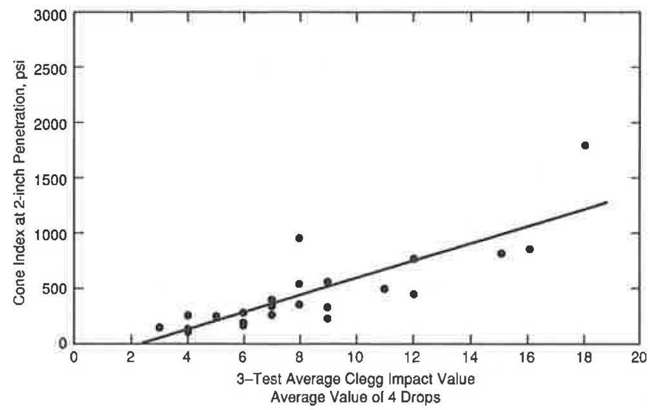

FIGURE 7 CI2-CIV4 regression (all soils).

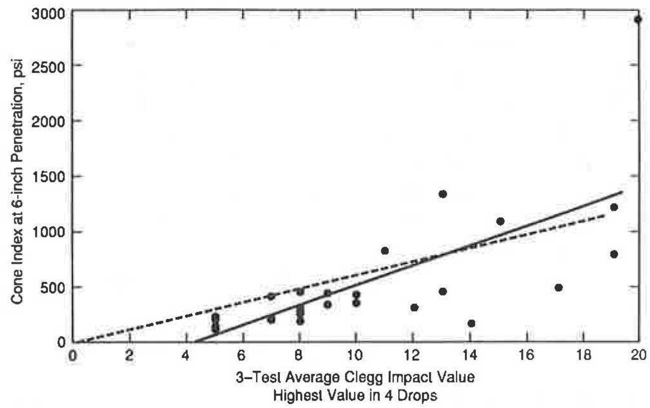

FIGURE 8 CI6-CIVHI regression (all soils).

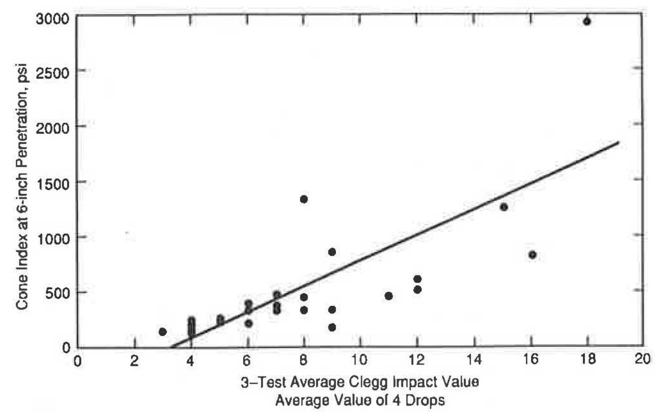

FIGURE 9 CI6-CIV4 regression (all soils).

be subjectively evaluated. Because soil penetration is limited to less than 2.4 in., its ability as a soil condition inference instrument should diminish quickly with depth. The adjusted R^2 and standard error statistics for the 2-in. cone index equations are better than their 6-in. cone index counterparts. Although this gives only a limited insight, the data appear to be consistent with the stated hypothesis. However, additional research should be conducted to quantitatively define the depth of confidence associated with the Clegg Impact Soil Tester in relatively homogeneous conditions. Clearly, the instrument may not be appropriate for the "hard over soft" condition when the softer underlayer will control the behavior of the soil surface under the action of traffic.

BOUNDARY CONDITION EFFECTS

The experimental procedure used here may impose boundary condition effects on the data that would not be present in the field. The steel compaction mold creates a near-field rigid boundary that may affect correlation results in two ways.

The impact of the Clegg Impact Hammer on the soil surface will create a dynamic wave that will return to the test location within the time interval needed to define the maximum deceleration of the impact hammer. Oscilloscope measurements for individual hammer drops indicate that the peak CIV value occurs in about 1 mS for stiff soils (CIV greater than 35) and in about 3.5 mS for soils with CIV values of 8. The return times for either compression or shear waves in moist soil would generally be less than 1 mS. The presence of these reflected dynamic waves is not apparent in oscilloscope data; hence, their effect on CIV values may be negligible. However, this condition would normally not be present in the field.

A near-field rigid boundary can influence cone penetration values developed in laboratory calibration studies using sands (*9*). The rigid boundary creates an artificial constraint not consistent with field conditions. This influence appears to be a function of overconsolidation ratio and the ratio of the diameter of the calibration mold and cone diameter. Whereas the soil in the field is confined by adjacent soil, the effects of a steel ring within 8.5-in. of a cone penetration test are different. For fine-grained soils, this problem may be more complex than for sand because moisture content directly affects the soil stiffness and lateral deformation properties. The overconsolidation and diameter ratios may also be important, as has been documented for sand.

The effect of these factors has not clearly been defined. Laboratory calibration and correlation studies are needed to continue to investigate the quantitative influence of these two boundary condition effects on the instrument responses.

CONCLUSIONS

The Clegg Impact Soil Tester was evaluated in a correlation study to better define its capability to assess soil response behavior. Regression relationships were developed using correlations between the maximum and average Clegg Impact Values obtained in four drops, CBR, and Cone Index (using the automated cone penetometer). Statistically significant and useful correlations between CIV and CBR were developed that were similar to expressions published for Australian soils. The correlation between CIV and CI values appears to be statistically significant, but more research is needed to determine if the precision is adequate for engineering applications.

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