Automated Cone Penetrometer: A Nondestructive Field Test for Subgrade Evaluation

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ABSTRACT

The results of a comprehensive program for the design, development, and field testing of an automated cone penetrometer are presented as an effective method for evaluating the condition of subgrade soils. Using this newly developed device, as many as 70 locations were tested at a site during an 8-hr day. The current automated penetrometer has a penetration depth of 406 mm (16 in.) and provides penetration resistance output readings at incremental 25-mm (1-in.) depths. The use of the automated cone penetrometer device, including its unique features for field use as demonstrated in a comprehensive field evaluation program conducted at Kelly Air Force Base, San Antonio, Texas, is described along with the results of a California bearing ratio (CBR) versus cone index correlation study. Analysis of the field data revealed a linear correlation between CBR and cone index with a correlation coefficient of 0.875. A parallel laboratory testing program was conducted on three fine-grained subgrade soil types obtained from the same test site. The laboratory test results were consistent with those obtained in the field. The use of the automated cone penetrometer technique and the correlation of its results to the CBR proved to be an effective, efficient, and reliable method for evaluating the subgrade soils encountered at the Kelly AFB site. The automated cone penetrometer holds promise as a good assessment tool for developing a statistical representation of subgrade conditions for fine-grained soils on both new and existing projects.

Dynamic and static cone penetration tests are widely used in deep subsurface investigations and have been adequately researched. However, penetrometers for evaluating shallow subgrade soil conditions have received little, if any, attention from researchers during the past decade, although the cone penetrometer, as an example, has proven to be a surprisingly accurate and efficient means for subgrade soil evaluation. The hand penetrometer has been used extensively especially in the military. However, the device needed development and improvement for better operation and more representative and reproducible results.

Dynamic penetration tests can be divided into two main types: constant rate of penetration and impact test. This investigation was concerned only with the first type, constant rate of penetration.

A penetrometer is basically an extremely simple device, a kind of calibrated index finger. It is a rod with a larger diameter conical tip that is forced vertically into the ground; the penetration resistance provides an indication of soil strength and is recorded as cone index (CI). The cone index is defined as the force per unit area of cone base required to push the penetrometer into the soil at a certain rate of penetration. Previous studies by Selig and Truesdale (1) and Nowatzki and Karafiath (2) have shown that CI is a function of rod size, shape, size of cone tip, and rate of penetration as well as soil type, density, and moisture conditions. On the basis of these studies and the report by Freitag (3), an automated cone penetrometer was developed as a field soil testing device.

Traditional methods of evaluating subgrade soil compaction and strength for existing and new highway projects include moisture-density, California bearing ratios (CBRs), and plate bearing tests. Although these strength tests are considered satisfactory for evaluating, directly or indirectly, the load-carrying capacity of in situ subgrade soil, the test procedures are rather lengthy, especially when conducted on poorly prepared surfaces or when conducted at certain depths below the ground surface, or both. Practically, only four to six locations can be tested for field CBR during an 8-hr workday. This presents a problem in getting statistically representative values particularly when there is some variability in soil type, moisture, and compaction conditions. Using the newly developed device, as many as 70 locations can be tested at a site each day.

The objective of this study was to develop an efficient, reliable means of subgrade evaluation, namely, the automated cone penetrometer; to establish a data interpretation process; and to correlate its results in terms of CI to a well-defined, widely used measure of soil strength.

DEVELOPMENT

The automated cone penetrometer device was developed as part of a U.S. Air Force-sponsored program designed to investigate unprepared and semiprepared soil runways as an alternative launch and recovery site for aircraft. The device developed provides the means for a quick, yet reliable, evaluation of the subgrade soil under various conditions.

The penetrometer consists of a shaft 9.4 mm (3/8 in.) in diameter with a 3.23-cm^2 (0.5-in.^{2}) base area and a 30-degree tip-angle cone at the top for shearing the soil while undergoing penetration. The penetrometer was mounted in a servo-drive electrohydraulic system that could maintain a constant rate of penetration [32 mm/sec (1.25 in./sec) was used]. The hydraulic actuator was mounted on a reaction frame that was attached to the front bumper of a vehicle through two hydraulic jacks that were controlled by the electrohydraulic system to lower the reaction frame at the test location and retract it during vehicle travel (Figures 1 and 2). The vehicle weight provided a maximum reaction of 1,800 lb to the frame.

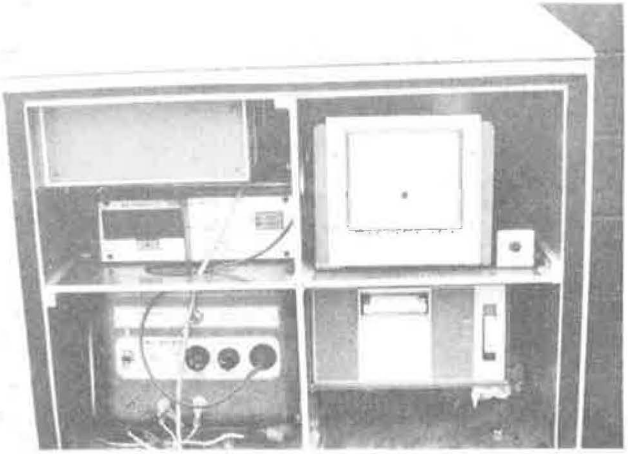

FIGURE 1 Autopenetrometer.

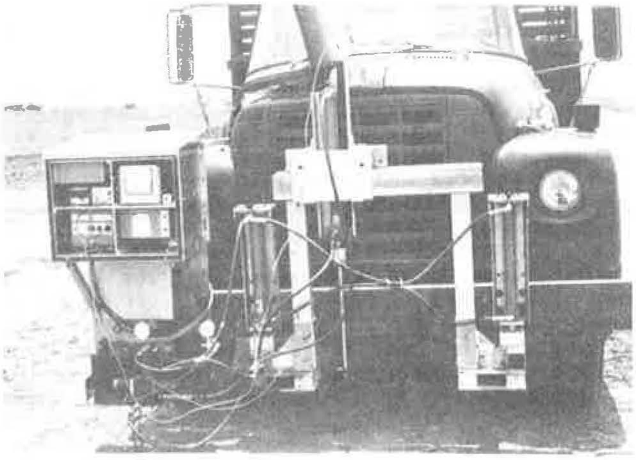

FIGURE 2 Autopenetrometer on traveling vehicle.

The penetrometer mounting arrangement permitted multiple penetration tests along the frame's cross-beam centerline at the test location without moving the vehicle. During the test program, three penetration tests, 8 in. apart, were performed at each test location. Limit hydraulic switches permitted the penetrometer to penetrate to a maximum depth of 406 mm (16 in.) measured at the base of the penetrating cone tip. Figure 3 shows the penetrometer during the test operation. Figure 4 is a schematic showing the essential features of the penetrometer.

The soil's penetration resistance force was measured through a load cell mounted between the penetration rod and the hydraulic piston. The penetration travel was measured using a linear variable differential transducer (LVDT) arrangement mounted to the hydraulic actuator. Both penetration resistance and travel were recorded on a paper tape recorder that provided a continuous printout of the results in pounds and inches, respectively. Penetration resistance in pounds was subsequently converted to cone index (CI) in psi using the cross-sectional area of 0.5 in.^{2} of the base of the cone.

FIGURE 3 Automated penetrometer ready for testing operation.

The automated penetrometer ran on the vehicle's 12-volt DC battery, and the test operation was performed by one driver-operator.

DATA INTERPRETATION

The test data could be interpreted directly for any particular depth from the continuous recorder printout. Distinct soil stratification and layer transition, due to changes in soil type, moisture, or compaction, could be observed. In such cases it may be desirable to distinguish the results for each strength zone.

During the field testing phase of this study and during particular periods, it was observed that the upper 15 to 20 cm (6 to 8 in.) was generally of higher strength than the lower portion. Consequently, in determining cone penetration resistance, three different determinations were made:

1. Average penetration resistance (psi) for the first 8 in. of penetration,
2. Average penetration resistance (psi) for the next 8 in. of penetration, and
3. Average penetration resistance over the full 16-in. depth of penetration.

To calculate a representative penetration value for the 16-in. depth, a simple computer-programmed, statistical procedure was followed in order to eliminate data scattered beyond a defined statistical range. The procedure assumes that the penetration readings at a particular location were of a normal population with T-probability distribution. The procedure checked whether the calculated mean of the readings was within 10 percent deviance from the true mean, with 95 percent degree of confidence. The calculated mean was accepted if it met this requirement. Otherwise, readings that were more than the mean plus the standard deviation, or less than the mean minus the standard deviation, were removed, and a new mean was calculated for the rest of the data. The overall cone index for a location is the average of the three penetrations at that location.

FIELD TESTING PHASE

An extensive field testing program was conducted at Kelly Air Force Base, San Antonio, Texas. Soil

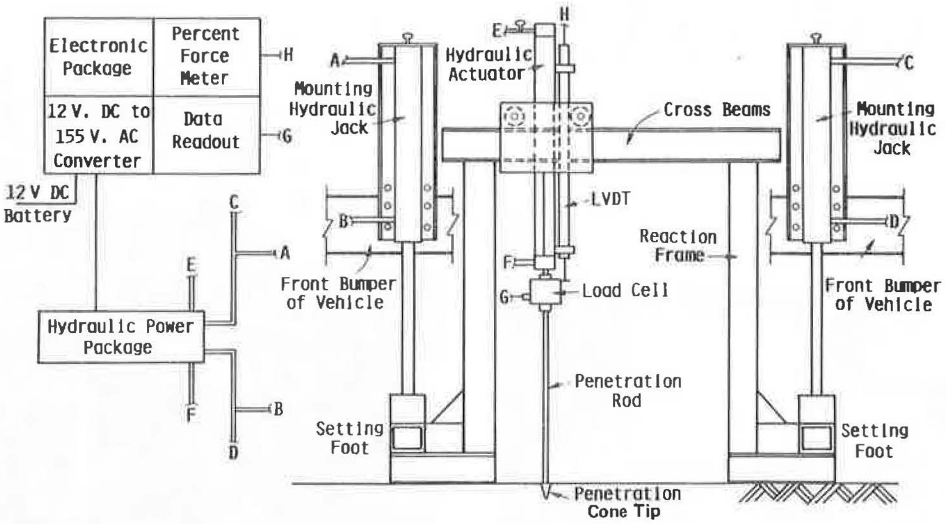

FIGURE 4 Schematic of automated cone penetrometer.

strength profile maps were made for soil runway strip and taxi areas using the automated cone penetrometer. Figure 5 shows an example of these maps. Field California bearing ratio (CBR) tests were performed at two different depths at 30 locations for which cone penetrometer results were also obtained. The penetration resistance values were taken at the depths where CBR tests were performed. However, the penetration resistance at the deepest point of the penetrometer test was taken when the depth of the CBR test was 406 mm (16 in.) or more. An average of three penetrations was used for the CBR-CI correlation analysis. The results of these field tests are given in Tables 1 and 2; Table 1 gives the tests run in June 1982 and Table 2 gives those run in July 1982.

The data in Tables 1 and 2 are for various fine-grained soils encountered on site (silty clay and clayey silt). CBR values ranged from 3.8 to 30.0 for data obtained in June (Table 1), and from 7.5 to 46.4 for the July period. The increase in strength range was due to the relatively dry weather between periods of testing.

The results in both tables are shown in Figure 6. When data in Figure 6 are fitted to a linear relationship between CBR and CI (in psi), the following relationship is obtained:

$$\mathrm{CBR} = 0.86 + 0.015\ \mathrm{CI} \quad \text{with correlation coefficient } r = 0.875 \qquad (1)$$

It should be noted that Equation 1 is the linear regression function for data obtained for various conditions of soil type, moisture, density, and postcompaction environment. Also, unavoidable elapsed time between CBR and penetration tests during the testing program may have been responsible for some of the scatter in data.

The CI-CBR correlation previously developed by the U.S. Army Corps of Engineers (4) for the hand cone penetrometer is shown in Figure 6. It should be noted that cone tip dimensions are different from those of the one used in this study. The different trend of that correlation may be attributed to the limited capability of the hand penetrometer to main-

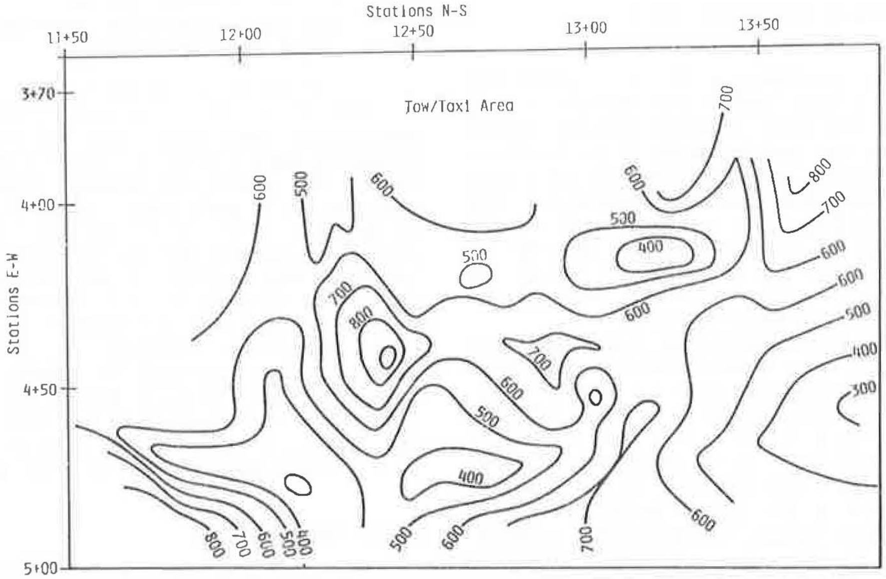

FIGURE 5 Soft soil test area strength contours, cone index (CI) in psi.

TABLE 1 CBR and CI Field Data, June 1982

Location No.	Unified Soil Classification	Average Field Moisture Content W (%)	Average Field Dry Unit Weight γ_D (pcf)	Depth of CBR Measurement (in.)	CBR (%)	CI (psi)
1	CL	26.5	90.8	5.0	7.5	390
1	CL			20.0	11.8	640
2	CL	25.9	88.05	7.0	20.5	1,044
2	CL			18.0	16.0	952
3	CL	25.0	89.1	5.5	9.2	566
3	CL			15.0	11.9	760
4		9.7	110.0	21.0	10.5	406
5		16.4	99.3	5.0	13.0	716
5				21.0	14.2	1,082
6	CL	20.0	100.2	4.5	4.9	330
6	CL			17.0	16.3	804
7	CL	25.3	88.0	9.0	3.8	178
7	CL			16.5	23.2	1,590
8		21.2	95.5	18.0	9.2	864
9		16.2	101.0	3.0	10.9	428
9				22.0	10.0	834
10	CL			5.5	9.8	314
10	CL			17.0	11.7	626
11		20.5	93.1	3.5	6.6	326
11	CL			21.0	14.6	816
12	CL	20.0	94.6	5.5	6.0	360
12	CH			15.0	8.1	454
13	CL	16.8	97.7	4.5	11.5	324
13	CL			19.0	7.8	640

TABLE 2 CBR and CI Field Data, July 1982

Location No.	Unified Soil Classification	Average Field Moisture Content W (%)	Average Dry Unit Weight γ_D (pcf)	Depth of CBR Measurement (in.)	CBR (%)	CI (psi)
14	CL	11.6	96.8	4.0	46.4	1,824
14	CL			20.5	20.7	1,270
15	CL	9.2	103.9	3.5	40.0	2,482
15	SM			19.0	12.8	712
16	CL	15.0	97.5	20.0	22.3	966
17	CL	14.1	99.5	3.5	26.3	1,548
17	CL			20.0	10.2	796
18	CL	10.3	101.8	4.0	24.2	2,004
18	CH			16.0	12.2	1,276
19	CH	8.7	100.8	5.0	33.8	1,636
19	CL			19.0	10.0	800
20		8.4	99.2	4.0	45.0	2,502
20	CH			20.0	12.0	730
21	CH			5.5	23.0	1,810
21	CH			24	7.5	1,232
22		12.3	98.5	5.0	19.5	1,482
22				16.0	18.5	1,388
23	CL	12.1	102.0	6.5	11.8	1,010
23	CL			6.5	14.2	1,010
23	CL			19.0	10.0	1,002
24		12.9	99.6	5.0	31.0	1,432
24	CH			18.0	16.8	1,430
25	SW-SM	5.1	111.6	8.0	15.8	946
26	CH	12.5	103.8	5.5	15.2	980
26	CL			18.0	23.5	1,358
27	CL	8.2	110.1	5.0	32.0	2,392
27	CL			21.0	18.7	1,182
28	CH	9.8	105.4	5.5	28.3	1,830
28	CL			16.0	13.0	1,404
30	CL	6.7	115.2	5.0	32.5	2,104
31		10.7	107.4	5.0	36.5	2,102
31	CL			20.0	11.5	1,168

tain a uniform rate of penetration when testing relatively hard soil.

LABORATORY TESTING PHASE

A parallel laboratory testing program was designed and conducted to establish the degree of correlation between laboratory CBR (as compacted ASTM D-1883) and laboratory cone penetrometer tests on similar soil specimens. CBR specimens were prepared in molds 152 mm (6 in.) in diameter and 178 mm (7 in.) high using standard Proctor compaction energy.

The penetration test was performed using a rod-and-cone penetrometer similar to that used in the field. The penetration shaft was mounted on an electrohydraulic materials testing system (Instron) shown in Figure 7. The Instron provided a constant penetration rate of 32 mm per second (1.25 in. per second). After each sample was tested for CBR, it was subjected to five penetration tests at the center and 38 mm (1 1/2 in.) off center in four locations. The penetration-resistance force results were recorded on x-y graph paper. Figure 8 shows an example of recorded test results. Zero penetration was designated at a position where the penetration cone

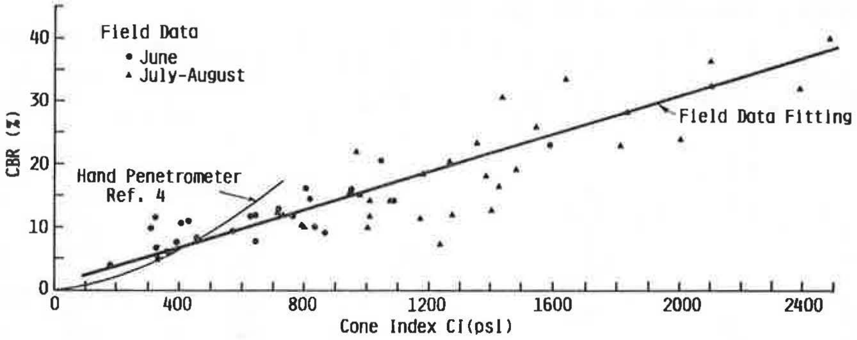

FIGURE 6 Correlation of CBR and CI from field data.

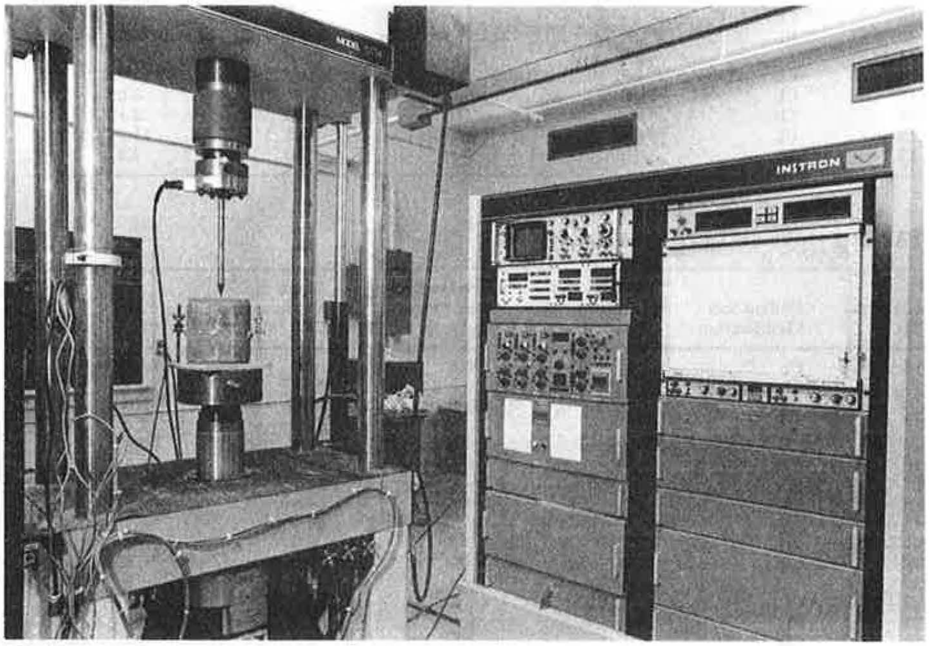

FIGURE 7 Laboratory test setup.

was set in the soil mold so that its base would be at the surface of the soil sample. The penetration test was started from that position at the specified rate for the full depth of the sample. This procedure avoided the effect of transition zones usually caused by the cone entering the soil sample and simulated the field test procedure. The penetration and resistance force were measured by an actuator-mounted LVDT and a 13.3-KN (3,000-lb) capacity load cell, respectively.

It was observed that penetration resistance varied somewhat with soil depth, reflecting soil compaction stratification in the mold. An average value was calculated to represent penetration resistance for each sample.

Four soil types encountered in the field were used in this testing phase of the study. Figure 9 shows the gradation curve for these soils, and Figure 10 shows the general relationship of CBR (as compacted) and compaction water content.

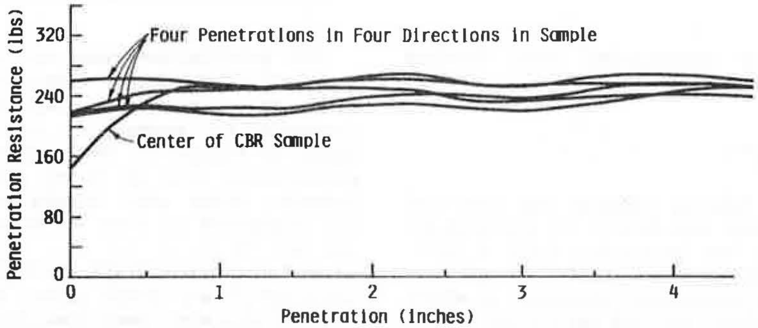

FIGURE 8 Typical penetration-resistance curves for laboratory samples.

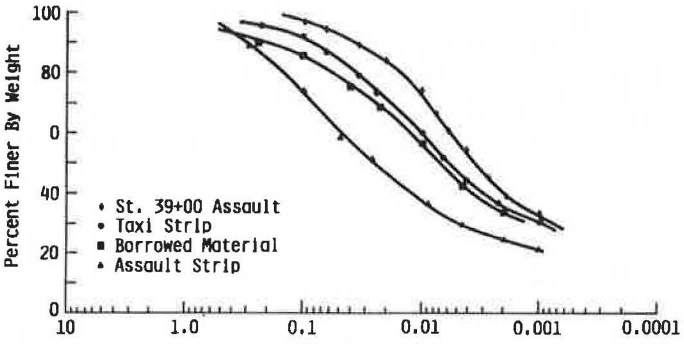

FIGURE 9 Grain size analysis results for sample soil.

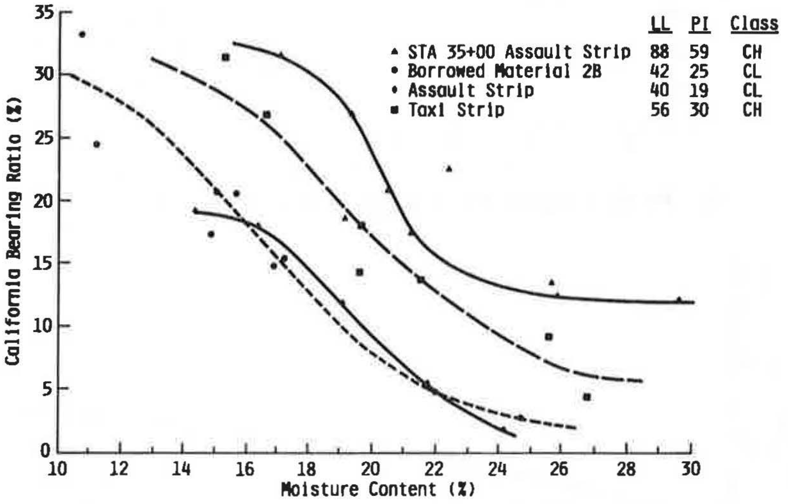

FIGURE 10 CBR versus moisture content variations for laboratory prepared soil samples.

The laboratory test results shown in Figure 11 have a general trend similar to that of the field data. The regression line developed from field data is shown in Figure 11 and illustrates that trend.

Given the nonhomogeneous nature of subgrade soils in general, Figure 6 and Equation 1 show good correlation between CI and CBR. The quick and efficient test procedure of the automated penetrometer along with Equation 1 provide the engineer with a highly reliable, effective means of evaluating fine-grained subgrade strength conditions.

EFFECT OF RATE OF PENETRATION

During the course of this study there was concern about the effect of the slower rate of penetration,

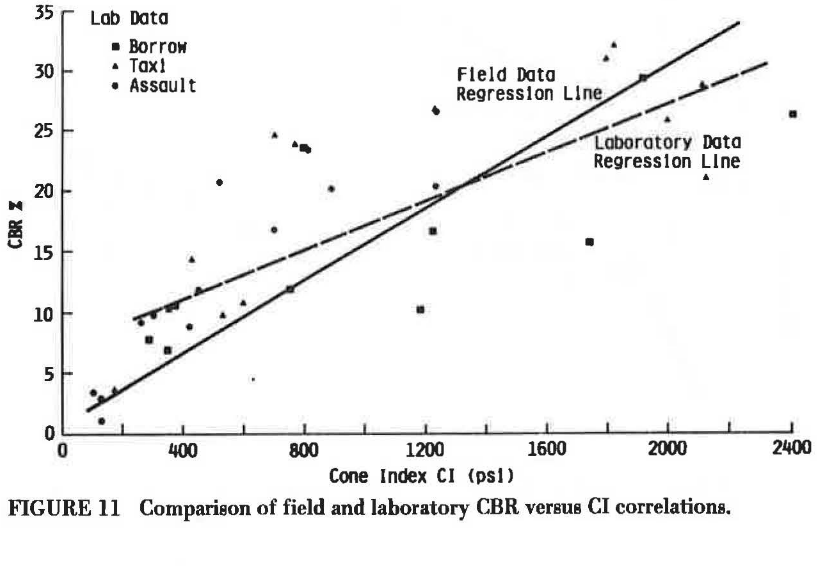

FIGURE 11 Comparison of field and laboratory CBR versus CI correlations.

which could result from relatively hard subgrade conditions, on measured penetration resistance. Different-rate penetration rate tests were performed on two soil samples in the laboratory. The penetration rate was varied between 6 mm (0.25 in.) and 32 mm (1.25 in.) per second. The results are shown in Figure 12. Freitag (3) and Selig and Truesdale (1) have investigated the same relationship in previous studies. Figures 13 and 14 show their findings. Figures 12-14 show that the measured fine-grained soil resistance to penetration varied by approximately 0 to 10 percent for a change in penetration

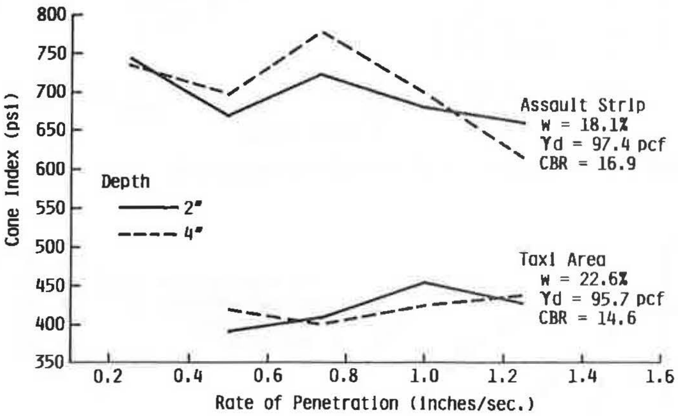

FIGURE 12 Variation of CI with cone penetration rate.

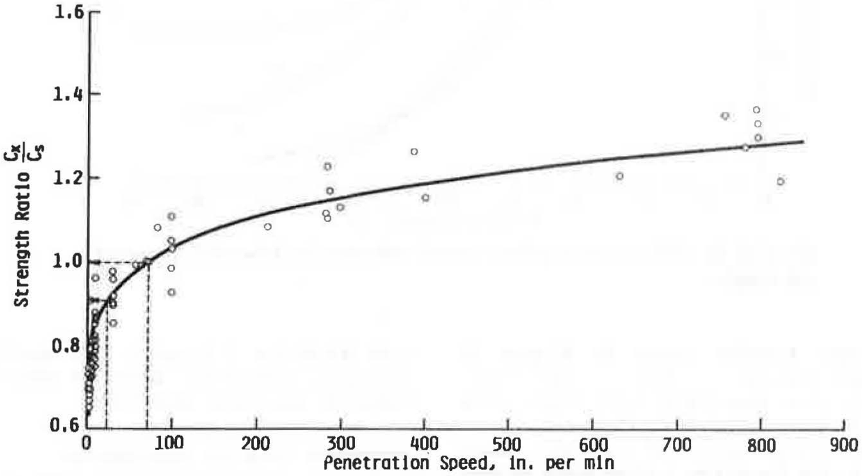

FIGURE 13 Variation in penetration resistance with penetration rate *(3)*.

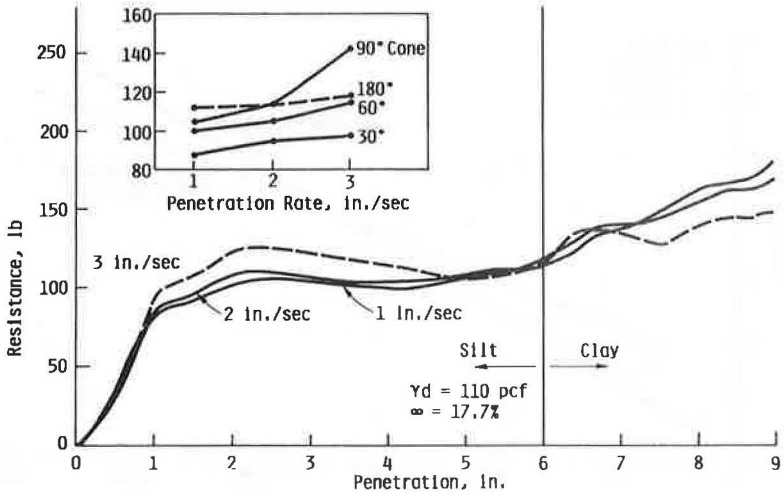

FIGURE 14 Variation in penetration resistance with penetration depth and rate *(1)*.

rate of 6 mm (0.25 in.) to 32 mm (1.25 in.) per second. However, these apparent variations in soil resistance could also be attributed to the nonuniformity of the soil, even when laboratory controlled specimens are used. The actual change in penetration rate for the automated penetrometer used in field tests was smaller than shown in Figure 12.

CONCLUSIONS

On the basis of experience gained from use of the automated cone penetrometer as a tool for assessing subgrade strength conditions at the Kelly AFB test site, and recognizing the range of soil types and strengths (CBRs between 5 and 46), the following conclusions are drawn:

1. An existing device, the cone penetrometer, has been improved through automation to evaluate subgrade soil conditions. The resulting technique and approach provide rapid, reliable, and reproducible results. The new device has a higher load capacity to test stronger subgrade soil than have existing hand-held penetrometers.
2. Results of correlation studies between the cone penetrometer tests and CBR tests indicate a consistent and definable relationship.
3. This improved test technique can be used to evaluate subgrade soil strength conditions under existing pavements as well as to provide a quality control technique for new pavement subgrade preparation.
4. The test technique does not require any special soil surface preparation and is considered nondestructive in comparison with other types of strength tests when performed at various depths below ground surface.
5. The consistency and efficiency of the test technique offer a good approach to the statistical presentation and evaluation of field data, thus ensuring a better soil strength condition evaluation to a proper depth.

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Rapid Determination of Base Course Strength Using the Clegg Impact Tester

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ABSTRACT

The Clegg impact tester was developed in Australia in the mid-1970s and is commonly used for density control during compaction. However, studies show that this device may be useful for measuring the strength of a wide variety of soil types. The project discussed here investigated this potential use of the Clegg impact tester. It is also part of a larger effort to develop a feasible procedure for evaluating gravel roads before paving. This device is particularly suited for the job because it is quick and simple to operate, portable, and inexpensive. Furthermore, results of this study show that Clegg impact values (CIVs) accurately predict pavement performance. In many cases CIV may be converted to an equivalent California bearing ratio value. Guidelines for testing are discussed, but additional research is required to refine the procedure.