Moisture and Density Effect on Cone Index

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ABSTRACT

CONE index, a measure of the penetration resistance of a soil, is affected by many factors including soil density, moisture content, and soil type. The effect of each of these three variables on cone index was investigated and discussed. Based on experimental data, an equation for cone index as a function of moisture content and density was developed for each soil type considered.

INTRODUCTION

Penetration tests were developed as fast and simple methods for obtaining information on *in situ* soil strength. A penetration test involves driving a penetrometer into the soil at a certain rate and recording the resisting force exerted by the soil on the penetrometer. The penetration tests were not initially standardized, which led to the evolution of a number of different tests using a variety of penetrometers.

One of the penetrometers which has seen varied applications is the cone penetrometer developed by the United States Army Corps of Engineers Waterways Experiment Station to determine soil trafficability (WES, 1948). The cone penetrometer consists of a 30 deg circular cone with a 3.2 cm^2 (0.5 $in.^2$) base area. The cone index is measured as the force per base area required to penetrate this cone into the soil at the rate of 1829 mm/min (72 in./min). The cone index thus determined provides some indication of the shear resistance of the soil which in turn depends upon the strength properties of the soil.

The cone penetrometer has been employed for various applications, including prediction of the tractive capability of an off-road vehicle (Freitag and Richardson, 1968; Wismer and Luth, 1972); characterization of soils in terms of crop growing ability (Raghavan and McKyes, 1977); determination of resistance to root penetration and seedling emergence (Bowen, 1976; Taylor and Gardner, 1963; Morton and Buchele, 1960); prediction of draft force (Johnson et al., 1978; Gill and Vanden Berg, 1968); and assessment of compaction caused by vehicle traffic (Sloane, 1973; Raghavan and McKyes, 1977; Chesness et al., 1972). Cone indices were also used to determine the effect of wheel size and vehicle weight on soil compaction, as well as earth embankments and foundations.

Previous studies examining the factors affecting cone index have shown that moisture content, density, and soil type can have considerable influence on the penetration resistance (Chesness et al., 1972; Wells and Treesuwan, 1977; Mulqueen et al., 1977; Smith, 1964; Knight, 1948). Very few studies have investigated the penetration resistance of soils at low moisture contents at which most agricultural, forestry, and construction operations are carried out. A more comprehensive understanding of how cone index is affected by moisture content, density and soil type is extremely important for extensive use of cone penetrometers, particularly in compaction-oriented studies. Therefore, the overall goal of this study was to investigate the effect of moisture content, density, and soil type on cone index and to develop empirical models relating these variables.

PROCEDURE

Cone penetration tests were performed using five different idealized soil types at different moisture contents and densities. The five soil types were obtained by mixing known percentages of zircon sand and fire clay. These soil types were: 100 percent clay, 75 percent clay - 25 percent sand, 50 percent clay - 50 percent sand, 25 percent clay - 75 percent sand, and 100 percent sand. A procedure similar to that of the Proctor compaction test was used to prepare soil samples (Lambe, 1951). An aluminum cylindrical mold of 15.2-cm (6-in.) diameter, 20.3-cm (8-in.) height, and 0.64-cm (0.25-in.) wall thickness was used for forming the soil sample. Compactive efforts were applied with a 4.3-kg (9.5-lb) drop hammer at a drop height of 30.5 cm (12 in.). Three different compaction levels were attained by using 3, 6, and 12 blows/layer.

The procedure followed for the tests is as follows. First, the mold was weighed empty. Soil sample was prepared by placing soil in the mold in layers and by applying a predetermined number of blows/layer. The mold with soil sample was weighed to determine average dry density. Penetration test was then conducted on the soil sample. Average moisture content (dry basis) of sample was determined by taking small samples from the mold. Tests were repeated twice on freshly prepared soil samples at the same moisture content and compactive effort. Additional tests were conducted in a similar fashion on soil samples prepared at two other compaction levels maintaining same moisture content. When the nine tests at three different compaction levels were complete, the moisture level of the soil was raised by adding water in a fine mist form and mixing thoroughly. Additional tests at different moisture levels were conducted as described

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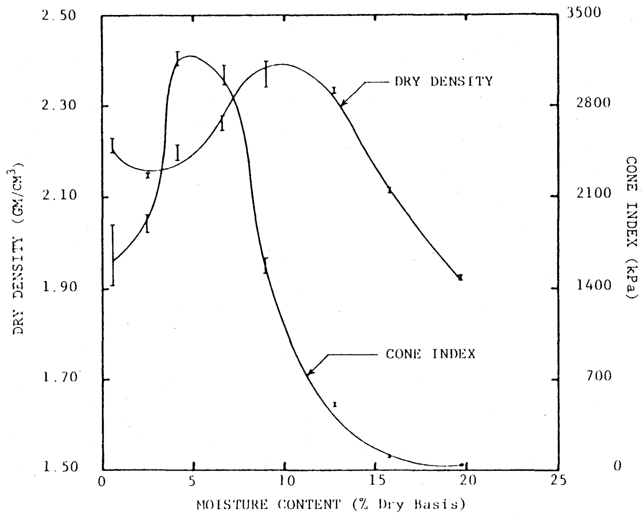

FIG. 1 Effect of moisture content on dry density and cone index for 50 percent clay - 50 percent sand at 12 blows/layer.

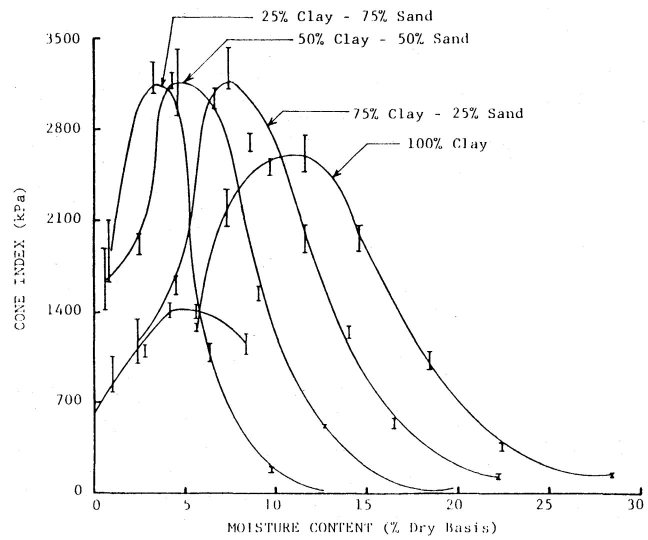

FIG. 2 The influence of soil type on the cone index - moisture content relationship. (12 blows/layer).

earlier. The moisture levels were selected to provide a reasonable number of observations in the range of 0 to 20 percent moisture level.

The ASAE standard cone penetrometer with a base area of 3.2 cm² (0.5 in.²) and an Instron testing machine, Model TM-S 3111, were used for penetration tests. The soil mold was placed on the testing machine and the cone penetrometer was driven 17.0 cm (7.5 in.) into the center of the mold at a rate of 1270 mm/min (50 in./min). The penetration resistance was recorded simultaneously as a function of depth. From the recorded data, the cone index value was determined by averaging the penetration force for the first 15.2 cm (6 in.) and dividing by the base area of the cone, as stated in the ASAE Standard 313.1 (ASAE, 1980). Even though the recommended penetration rate for the standard cone index test is 1829 mm/min (72 in./min), for this study a penetration rate of 1270 mm/min (50 in./min) was used. This somewhat lower penetration rate was the maximum possible on the Instron testing machine. The results of previous studies (Turnage, 1970 and 1974) showed that this difference in penetration rate had no effect on the penetration resistance for coarse-grained soils and minimal effect for fine-grained soils.

Thus a series of penetration tests were performed for each soil type. Seventy-two penetration tests each were performed on soil samples with 100 percent clay, 75 percent clay - 25 percent sand, and 50 percent clay - 50 percent sand. Fifty-four and 63 tests were performed on soil samples with 25 percent clay - 75 percent sand and 100 percent sand, respectively. A detailed description of the procedure and the test data are presented in Ayers (1980). The test procedure employed during this study was similar to the procedure used at the Waterways Experiment Station (Knight and Green, 1959; Knight, 1961).

RESULTS AND DISCUSSION

Density and Cone Index vs. Moisture Content

As a result of the compaction and penetration tests, dry density - moisture content and cone index - moisture content relationships were developed. Typical relationships for 50 percent clay - 50 percent sand at a compaction effort of 12 blows per layer are shown in Fig. 1. In this graph, the ranges of observations at particular moisture contents are shown and curves are drawn generally through these ranges.

The effect of varying soil moisture content on dry density and on the cone index can be easily observed in Fig. 1. Each curve is hump-shaped, with a maximum dry density of 2.37 g/cm³ attained at a moisture content of 10 percent and a maximum cone index of 3300 kPa (478 psi) attained at a moisture content of 5 percent. The characteristic shape of the cone index - moisture content curve has been observed by Knight (1948). Wells and Treesuwan (1977) also reported this trend when cone index was measured for a soil over a range of moisture content keeping the density constant.

From Fig. 1, it can be seen that the maximum cone index does not occur at the moisture content that produces the maximum dry density. This phenomenon has been observed by Knight (1948), Hough (1957), and Smith (1964). Preliminary studies performed by Ayers (1980) show that maximum cone index occurs at a moisture content producing the maximum shear strength as determined by the triaxial compression test.

At a compaction effort of 12 blows per layer, an increase in the percentage of clay in the soil sample was found to raise the moisture content at which the maximum cone index occurs (Fig. 2). Cone index values for 100 percent sand were significantly lower than those obtained for soil types containing a certain percentage of clay. For a given soil type, an increase in compaction effort produced an increase in the maximum cone index attained as shown for 50 percent clay - 50 percent sand in Fig. 3.

Cone Index vs. Dry Density

For all soil types, except for 100 percent sand, the influence of moisture content on the cone index - dry density relationship was consistent. A typical relationship for a soil type of 50 percent clay - 50 percent sand is shown in Fig. 4. At low moisture contents (2.6 percent, 4.4 percent, and 6.7 percent), values of cone index appear to increase exponentially and at a high rate with dry density. Increases in moisture content, to 8.8 percent and 11.8 percent, resulted in a more linear relationship between cone index and dry density. Also, the rate of increase of

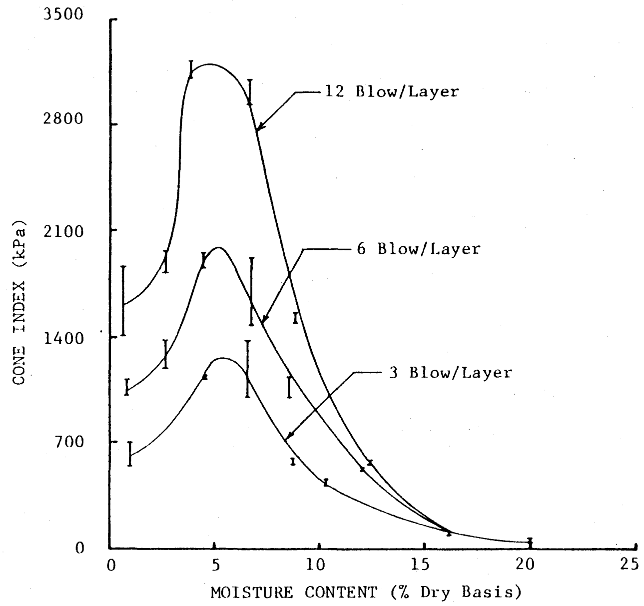

FIG. 3 The influence of soil compaction effort on the cone index -moisture content relationship (50 percent clay - 50 percent sand).

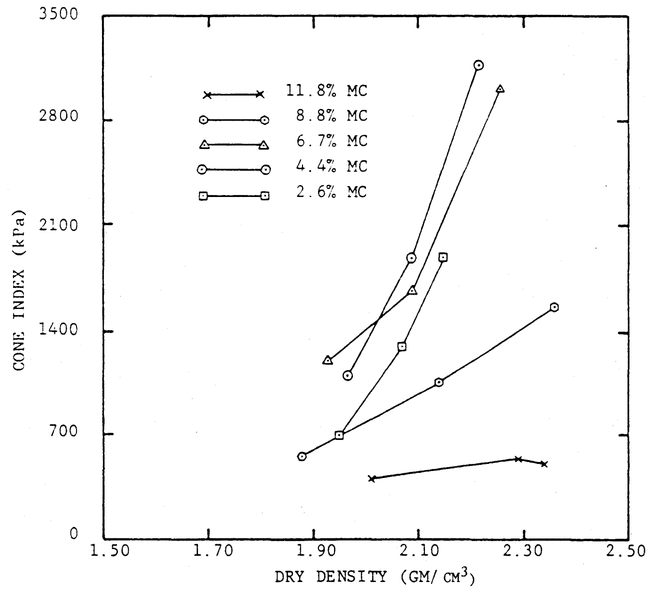

FIG. 4 The influence of moisture content on the cone index - dry density relationship for 50 percent clay - 50 percent sand.

cone index with dry density was observed to decrease considerably at higher moisture contents. Similar behavior was observed by Mulqueen et al. (1977). For 100 percent sand the cone index - dry density relationship was found to be independent of moisture content (Ayers, 1980).

Cone Index Model

One of the objectives of this study was to develop a mathematical relationship for cone index in terms of density and moisture content for different soil types. After visualizing the cone index - moisture content - density relationship for a specific soil type as a three-dimensional surface, as shown in Fig. 5, several possible prediction equations were considered. Analysis of these equations for the prediction of cone index was performed using a non-linear least squares (Marquardt Method) statistical computer package, Statistical Analysis System (SAS). Goodness of fit and minimal complexity were the criteria used for selecting the model. The equation developed to represent te cone index - density - moisture content relationship is as follows:

$$CI = (C1 * DD^{C4}) / [C2 + (MC - C3)^2] \quad [1]$$

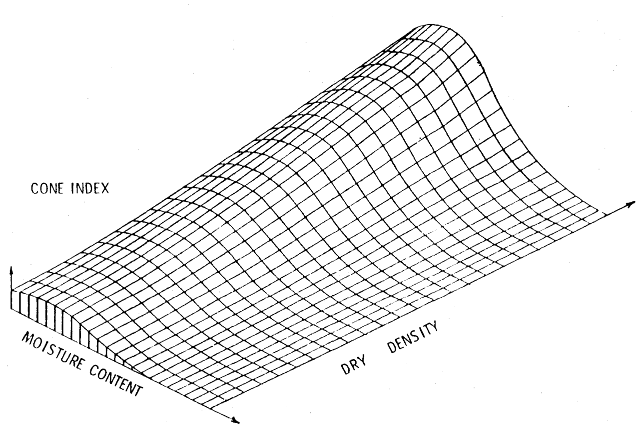

FIG. 5 Cone index - dry density - moisture content relationship as described by the cone index model for 50 percent clay - 50 percent sand.

where,

CI = cone index, kPa
DD = dry density, g/cm³
MC = moisture content, percent dry weight
C1, C2, C3, and C4 = constants to be estimated depending upon soil type.

This cone index model has some similarities to one developed by Chesness et al. (1972). However, equation [1] can be used for the entire moisture content range.

Equation [1] can be rearranged to predict the soil density if the cone index and moisture content are known, assuming the constants for that soil have been determined. The equation for dry density is as follows:

$$DD = [(CI/C1) \;\; C2 + (MC - C3)^2 \;\;]^{1/C4} \quad [2]$$

The constants for the cone index model, as determined by the statistical analysis, vary depending upon soil type. The values of constants for the different soil types considered in this study are shown in Table 1. The correlation coefficient, R^2, is an indicator of how well the equation fits the data and is also listed in Table 1. The R^2 values for the four soil types which contained some clay averaged 0.98, indicating that, by using this model, 98 percent of the variation in cone index can be accounted for by variations in the independent variables, density and moisture content (Hayes and Ligon, 1977). For sand the equation form yielded an R^2 value of 0.94. In general, this cone index model produced a much better prediction, in terms of R^2 value, than reported by previous investigators. The values of the model constants generated by the statistical analysis procedure were found to correlate with the percentage of clay in the soil type (Ayers, 1980).

TABLE 1. CONE INDEX MODEL CONSTANTS FOR EACH SOIL TYPE

Soil Type	C1	C2	C3	C4	R^2
100% clay	4540.9	31.94	9.21	6.37	0.985
75% clay - 25% sand	928.1	20.22	7.41	6.60	0.983
50% clay - 50% sand	82.39	9.47	4.77	7.50	0.978
25% clay - 75% sand	1.10	2.19	3.29	9.34	0.982
100% sand	1.58	17.72	5.54	8.92	0.940

CONCLUSIONS

The effects of density and moisture content on cone index were investigated for five different soil types. The conclusions from the study are as follows:

1 The cone index - moisture content relationship revealed that for a constant compactive effort, a maximum cone index is produced at a specific moisture content (Fig. 1).

2 The specific moisture content for maximum cone index depends on the soil type and increases as the percentage of clay in the soil increases (Fig. 2).

3 For a given soil type, the moisture content yielding the maximum cone index was less than the moisture content yielding the maximum dry density (Fig. 1).

4 The cone index - dry density relationship for soils containing a certain percentage of clay revealed that for low moisture contents, dry density had considerable influence on cone index values. At higher moisture contents, cone index was found to be less dependent on dry density (Fig. 4).

5 Statistical analysis shows that the empirical relationship developed between cone index, moisture content, and dry density is valid for the different soil types considered in this study.

6 The values of constants in the cone index model were found to depend on the percentage of clay in the soil type.

APPLICATIONS

The model described in this paper is based on results of tests conducted on prepared soil samples. If this model is to be used for predicting dry density in natural soils, the constants for each type of soil must be estimated. A density - cone index - moisture content relationship of the type developed (equation [2]) should enable one to make use of the cone penetrometer for soil compaction related studies. Also, the potential is evident that through future research the cone penetrometer may be used as an instrument to develop subsurface density profiles for *in situ* soils.

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