AN ECONOMICAL PENETROMETER FOR HIGH STRENGTH SOILS

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ABSTRACT

The Centre Cone Penetrometer was developed as a low-cost instrument suitable for compaction studies. Simple in design, this hand-held penetrometer uses a helical compression spring to relate applied force to a linear scale. A sliding friction disc or rider allows an operator to keep track of the maximum force required to penetrate each depth interval. Use of a smaller-than-standard-diameter cone increases the range of mechanical impedance readings up to 110 bars.

Tests completed on the instrument indicate a force detection accuracy of ±5% of the full-scale reading. A side-by-side field comparison with a relatively expensive digital recording penetrometer showed a correlation of 0.99 when maximum readings were considered per depth interval.

It is hoped that the low cost and convenience of this instrument will allow compaction surveys to be carried out more efficiently.

INTRODUCTION

Soil cone penetrometers have been used extensively for soil strength evaluation despite concerns about data interpretation (Mulqueen et al., 1977). Useful empirical relationships have been developed based on penetration resistance data, such as those related to crop root development (Taylor and Gardner, 1963). At the Soils Branch of the Alberta Environmental Centre, the relative simplicity, rapidity and cost-effectiveness of data collection have been considered to be sufficient arguments for the continued use of penetrometers. Indeed, time and budgetary constraints often dictate that detailed compaction studies are not carried out unless a convenient means of data collection is available. Therefore, an attempt has been made to provide an adequate system of interpretation of penetration resistance data, and to develop a penetrometer which is low in cost and suitable for use in compact soils.

This paper discusses the development of the Centre Cone Penetrometer (CCP) including design considerations, construction details and testing procedures.

INSTRUMENT DESCRIPTION

The general construction of the CCP is shown in Fig. 1. The major components of the instrument are illustrated except for the helical compression spring which is housed inside the PVC body.

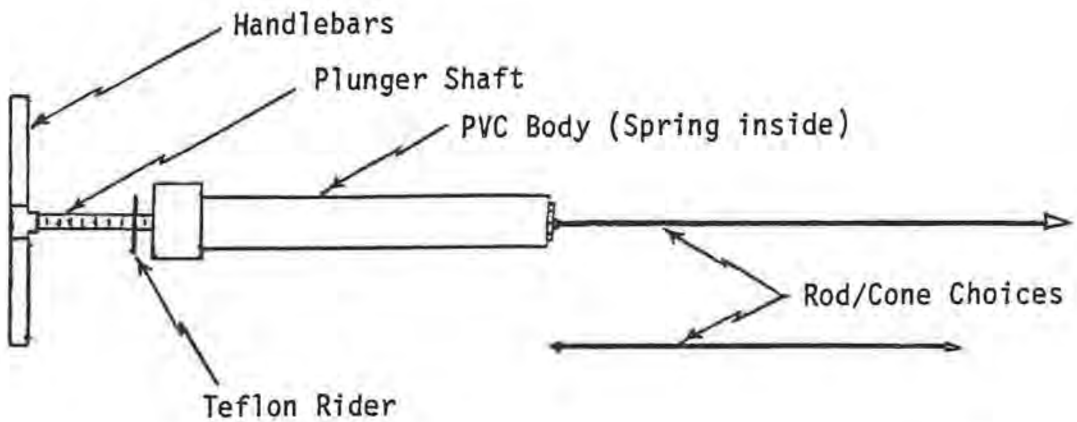

Fig. 1. Assembled instrument showing major components.

PVC was chosen for the penetrometer body because it is easy to machine, durable, low cost and lightweight. The base of the instrument body and the handlebars are suitably reinforced with steel.

The compression spring was specified to fit the geometrical constraints while providing a force-displacement characteristic to accomodate the average operator. It was designed for loads up to 710 N (160 lb) and so that there would be good resolution of the linear scale on the plunger shaft. The spring constant is about 6 N/mm.

Two different rod and cone assemblies may be attached to the penetrometer body. One, conforming to the American Society of Agricultural Engineers Standard S313.2, allows penetration resistance readings up to 55 bars with the use of a cone having a basal area of $129 mm^2$ (0.2 $in.^2$). The other assembly allows readings up to 110 bars with the use of a cone of half this area. Depths of 50 cm can be reached with the standard assembly and depths of 40 cm with the smaller cone and rod. With either assembly depth increments as small as 5 cm may be considered.

Two scales are stamped on the plunger shaft so that a reading in bars is possible while using either rod and cone combination. Jam nuts on the base of the plunger shaft are adjustable so that the no load displacement may be set to correspond to the first reading marks on the scales.

A teflon rider on the plunger shaft holds its position after force is released from the handlebars so that the maximum reading may be read easily for each depth interval penetrated. The rider is reset by pushing it back down to the base of the plunger shaft before the next reading is made.

DESIGN CONSIDERATIONS

One criterion of the proposed penetrometer was that its cost (parts and labour) be under $100. The design, therefore, had to incorporate off-the-shelf components and allow easy construction.

A limitation of commercially available hand-held penetrometers is their inability to penetrate very hard soils. Experience has shown that, during dry conditions and in areas where compaction is a suspected problem, mechanical impedance readings are frequently as high as 100 bars. Available penetrometers using cones with a basal area of 129mm^2, conforming to ASAE Standard S313.2, have an upper limit of 55 bars assuming that an operator can push with a force of 710 N (160 lb). Penetration resistance or Cone Index readings are defined by the equation C.I. = F/A, were 'F' is the applied axial force and 'A' is the cone's basal area. Since 'F' is limited by the force an average operator can apply, it follows that an increase in C.I. can be made only by decreasing 'A'. Accordingly, cones having a basal area of 64.5mm^2 (0.1 in.^{2}) were tested. A complicating factor was the need for a smaller diameter driving rod in order to maintain an adequate shoulder (distance between cone base and rod radii). In turn, use of a smaller diameter rod led to concern about buckling. The best compromise was to use the 64.5mm^2 cone with a 7.94mm (5/16") diameter driving rod, but to limit the rod length to 40 cm. That arrangement allowed the available 710 N force to correspond to a C.I. value of 110 bars.

Another requirement of the CCP was that it have a maximum reading indicator. This feature, lacking on many commercial models, is considered important especially when evaluating barriers to root growth. The device retains the maximum reading for a measured depth interval and thus reduces the amount of judgement an operator must exercise and the associated error. The simple teflon rider described earlier has proved to be effective for this purpose.

Another concern with many of the available penetrometers is that their use causes undue operator fatigue. Some units are heavy and bulky to carry around. Many require an operator to bend nearly to the ground to force a cone to its maximum depth, and then to pull, while in a similar position, to extract the cone from the soil. The CCP weighs only 2.0 kg and is designed so that an operator never has to push from a height of less than 48 cm or pull from a height of less than 60 cm.

LOADING FRAME TESTS

The calibration of the CCP was checked in a loading frame which allowed displacement of the plunger to be accurately controlled while a platform balance registered the applied force to the nearest 4.5 N (1 lb.). For each force increment established by reading the platform scale display, a corresponding value was read from the plunger shaft scale. Thirty instruments were tested over 22 force settings. The number and magnitude of discrepant readings were charted.

Concern was expressed that operators might unwittingly apply uneven forces to the handlebars of the CCP, causing friction where the plunger shaft contacted the top cap of the instrument. The loading frame was used to establish how the instrument's force detection accuracy was affected by unbalanced loading. A special tee was placed on the top of the plunger so that loads could be applied at 13mm or 25mm from its centre. Again, force readings from the platform balance and the penetrometers' scales were compared for 22 force settings on 30 penetrometers.

The results of the loading frame tests for 0, 13 and 25mm off-centre loading are shown in Table 1. Note that there is little difference between results for the first two loading modes, but that the number of discrepant readings increased dramatically under the 25mm off-centre condition. There was a fourfold increase in the average error per reading. Even under this loading condition, no individual errors greater than 1 scale division on the plunger shaft were recorded. (Each scale division corresponds to 32 N; the force resolution is 16 N).

Table 1. Discrepant reading summary for loading frame tests

Off-centre distance [mm]	1/2 division error [%]	1 division error [%]	Total error [%]	Average error [N]
0	3.0	1.2	4.2	1
13	3.6	0.0	3.6	1
25	18.6	2.7	21.3	4

The number of discrepant readings increased not only with the degree of off-centre loading, but also with the magnitude of the applied load. Thus, it seemed likely that a linear relationship could be found between the average error recorded and the applied moment (load times off-centre distance). Fig. 2 shows the regression line relating average error to applied moment for the 25mm off-centre loading condition. The positive y-intercept indicates that some error was not caused by the applied moment; friction caused by the teflon rider may have been a contributing factor.

Based on the loading frame tests, the largest individual errors were one scale division in magnitude. Average errors were much smaller and it seems likely that with a few refinements and greater quality control the largest errors might be cut in half. However, based on current data, the accuracy is about ±5% of the full-scale reading.

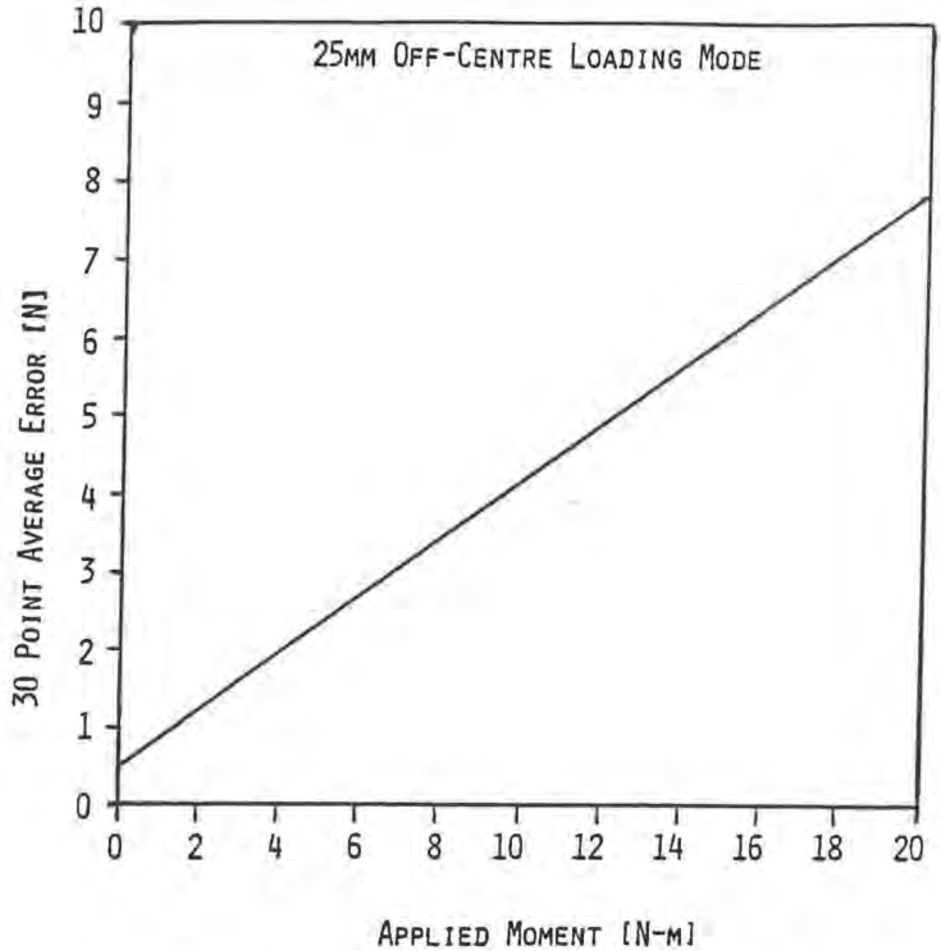

Fig. 2. Least squares regression line of average error versus moment for the 25mm off-centre loading mode.

OPERATOR TESTS

Having established the off-centre loading characteristic of the CCP, it was still necessary to determine if the average operator unwittingly would apply enough unbalanced force to the handlebars to cause significant errors. Operators performed tests in such a way that the actual forces they were applying were measured with a platform balance as they pushed penetrometers into a bucket of soil. Penetrometer readings were then compared with balance readings. This procedure was followed for six force settings, two different instruments, two rod and cone combinations and 10 operators.

Discrepancies between balance and instrument force readings were charted and analyzed (see Table 2). If off-centre effects were significant, instrument readings would have been statistically lower than balance readings. In fact slightly more of the observed discrepancies were positive, leading to the conclusion that errors due to off-centre loading were not significant in these test.

Table 2. Discrepant reading summary for operator tests

Error description	% of total readings	% of discrepant readings
1/2 division errors	24.6	68.3
1 division errors	11.4	31.7
All errors	36.0	100
Negative errors	15.1	41.9
Positive errors	20.9	58.1

The percentage of discrepant readings was higher during the operator tests than during loading frame tests. This would be expected since 10 different operators were asked to exercise judgement in establishing the applied forces and in reading both force scales. Significantly, all the discrepancies reported were still within one division on the plunger shaft scale.

SIDE-BY-SIDE FIELD COMPARISON WITH A DIGITAL RECORDING PENETROMETER

Another test was performed to compare the CCP with a solid state digital recording penetrometer (SSP) in side-by-side field measurements. The recording penetrometer was a Bush Recording Soil Penetrometer Mark I Model 1979 which retails for over $5000. The penetrometers were fitted with similar rods and cones. Readings were taken with a 10 cm spacing between individual penetrations. Four depth intervals were considered: 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm. For each interval the maximum reading was recorded. Two sites of significantly different soil strengths were selected and 120 data pairs were obtained from each. Each 10 pairs of penetrations were treated as a group and the data for each depth interval were averaged to reduce variability. Data from the two sites were combined to determine an overall correlation coefficient.

The 24 averaged points are plotted in Fig. 3. Note that the overall correlation coefficient was 0.99. The regression line with a slope of 0.97 and a y-intercept near the origin shows that the relationship between the two data sets is nearly one to one.

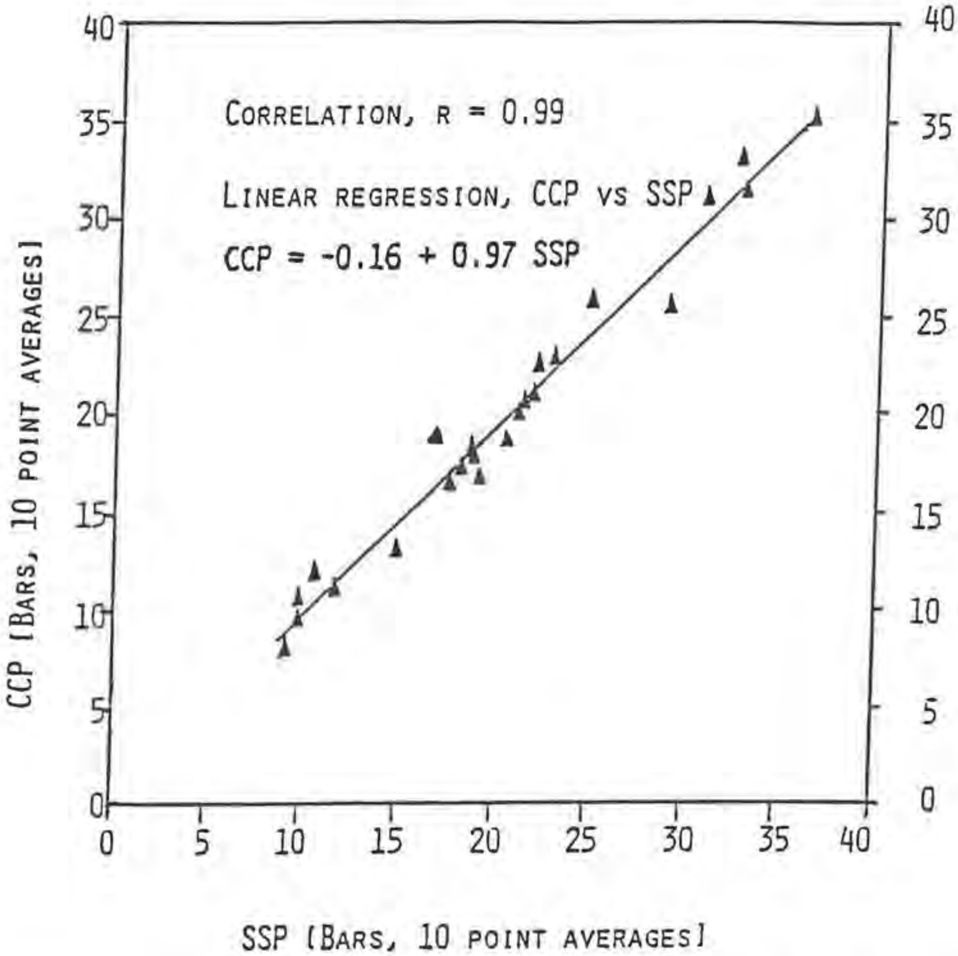

Fig. 3. Correlation of data obtained using the Centre Cone Penetrometer (CCP) and a solid state recording penetrometer (SSP) in side-by-side field tests.

CONCLUSIONS

A hand-held penetrometer was developed capable of measuring soil strengths up to 100 bars and costing less than $100.

Loading frame tests of the penetrometer showed an accuracy in force detection of ±5% of the full-scale reading.

Inaccuracy due to eccentric loading was not evident during operator tests.

Excellent correlation was found between averaged soil strength measurements taken with the new penetrometer and a digital recording penetrometer in side-by-side field tests.

LITERATURE CITED

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