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3. An analysis was made of the results of tests on 533 samples of soils which had been tested by the Highways and Local Government Department of South Australia. For these samples the linear shrinkage test had been carried out on material passing the No. 7 B.S. (No. 8 U.S.) sieve and California Bearing Ratio tests at 100 per cent of standard A.A.S.H.O. compaction had also been performed.

A correlation coefficient of -0.797 was found between linear shrinkage and the logarithm of the California Bearing Ratio, the regression equation being
log. (C.B.R.) = 1.68 - 0.085 (Linear Shrinkage) with standard error of estimate 0.25. The results of sieve analyses of these soils were not available.

4. There were available the results of tests on 159 samples of soil on which the California Bearing Ratio test at 95 per cent of Modified A.A.S.H.O. compaction had been performed, as well as linear shrinkage tests on the material passing No. 36 B.S. (No. 40 U.S.) sieve, and sieve analyses on the No. 7, No. 36 and No. 200 B.S. sieves. These results were examined by the method of linear multiple correlation and the regression equations, correlation coefficients and standard errors of estimates are shown in Table 2, where

Y = logarithm of California Bearing Ratio
X_1 = linear shrinkage from the liquid limit on material passing No. 36 B.S. sieve
X_2 = percentage passing No. 36 B.S. sieve
X_3 = percentage passing No. 7 B.S. sieve
X_4 = percentage passing No. 200 B.S. sieve

TABLE II

Regression equation	Correlation Coefficient	Standard error of estimate of Y
1. $Y = 1.99-0.042X_1-0.0009X_2+ -0.0051X_3-0.0016X_4$	0.732	0.241
2. $Y = 2.00-0.042X_1-0.0074X_2+ -0.0021X_4$	0.732	0.241
3. $Y = 2.06-0.046X_1-0.0074X_2$	0.724	0.243
4. $Y = 1.44-0.052X_1$	-0.656	0.265

The percentage passing the No. 36 sieve (X_2) had little effect on the estimate and equation 2. was used as the basis of an alignment chart for estimating the California Bearing Ratio.

5. It is realized that the California Bearing Ratio test is not in itself an entirely satisfactory basis for estimating the relations of the simpler tests to the actual stability of the soil. Further, the methods of statistical analysis used have been relatively simple and the work is now being extended to an examination of multiple curvilinear correlations between various tests, particularly with regard to the effect of the proportions of various particle sizes, in which case there is evidence that the relationship is not linear.

6. The objects of this investigation have been,

a) to obtain information of immediate value in the control of works in the field.
b) to establish relations between test methods preparatory to carrying out a field examination of pavement thicknesses and their relation to soil, traffic and climate.

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III b 3

DETERMINATION IN SITU OF THE SHEAR STRENGTH OF UNDISTURBED CLAY BY MEANS OF A ROTATING AUGER

LYMAN CARLSON
The Royal Swedish Geotechnical Institute

INTRODUCTION.

The shear strength of clay is usually determined in the laboratory from samples taken from different depths of the ground. In Sweden the investigation is generally carried out by means of unconfined compression test or cone test. Usually the shear strength, thus obtained, increases only slightly with the depth under the surface of the ground. It is often smaller than the "real" strength, calculated from slides that have occurred in the same soil. This discrepancy may depend partly on disturbance of the sample caused by the sampler, partly on changes in the sample due to decrease of pressure when the sample is extracted. The decrease op pressure is likely to have a considerable effect on the results as pointed out by S. Odenstand. 1)

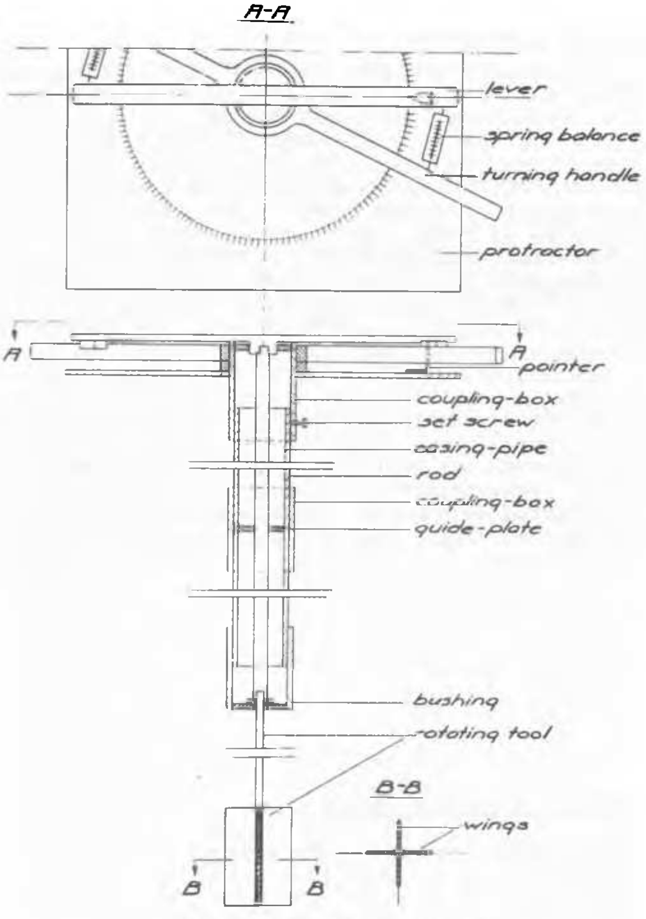
These errors can never be entirely eliminated when the investigation is carried out on extracted samples. The only possibility of avoiding them, especially the latter one, is to determine the shear strength directly in the ground. Such a method whereby both errors are practically eliminated, is being developed at The Royal Swedish Geotechnical Institute, and is described below. The experiments are still in an early stage, but the method, as now can be judged, seems full of promise.

Similar experiments are said to have been performed in Sweden by professor Carl Forssell and in Germany by Deutsche Forschungsgesellschaft für Bodenmechanik (Degebo). But as far as is known they seem not to have taken due consideration to the sensitivity of the clay to disturbance.

THE TESTING APPARATUS AND ITS METHOD OF APPLICATION.

In this early stage of the experiments the apparatus was constructed in a very simple manner. Essentially it consists of parts from the Swedish piston sampler 2) and the Swedish sounding auger. 3)

The apparatus is shown in fig. 1. At its lower end it consists of a rotating tool made up of a steelshaft on which four thin rectangular wings are welded. The tool is lengthened upwards by means of suitable extension rods, each one metre long. The whole rod is surrounded by a casing pipe also in one metre sections. The shaft of the tool has such a length above the wings, that when the tool is in the position shown in fig. 1, the wings will be in clay, which is not disturbed by the casing-pipe. Thanks to its thinness the tool itself does not appreciably disturb the clay to be tested.



The testing apparatus.

FIG. 1

The sections of the casing-pipe are joined by coupling-boxes, some of which are furnished with guide-plates for the turning rod. The shaft of the rotating tool is centred at its lower end by means of a bush fitted to the lower coupling-box. A protractor is mounted on the upper coupling-box which is located in position by means of a set-screw. At the same coupling-box a turning handle rests on a bearing. The turning rod is furnished with a lever, on which a pointer, for reading the protractor, is fastened. The lever is connected with the turning handle by means of two spring balances, so that when the turning handle is rotated, torsional moment is transmitted to the lever.

The apparatus is driven down into the ground by pressure or ramming. Before this procedure the turning handle, the uppermost coupling-box, and the parts attached to it are removed. In order to be protected while being driven down, the rotating tool is lifted, so that the wings rest against the lowest coupling-box.

When the soil layer to be tested is reached, the parts which were removed, are reassembled, and the rotating tool is pushed down to its lower position. The test proper is then carried out as follows (shown in fig. 2). The turning handle is turned at such a speed, that the velocity of the lever, controlled by means of a watch and the protactor, is kept constant. The forces, indicated by the spring balances, are noted at certain time intervals and, when the maximum readings are registered, the turning is stopped.

The testing apparatus during oparation.

FIG. 2

The apparatus is then driven down to the next testing depth, and the procedure is repeated.

THE SHAPE OF THE SURFACE OF RUPTURE.

Some simple experiments have been made in order to study the shape of the surface of rupture which is produced, when the tool is turned in clay.

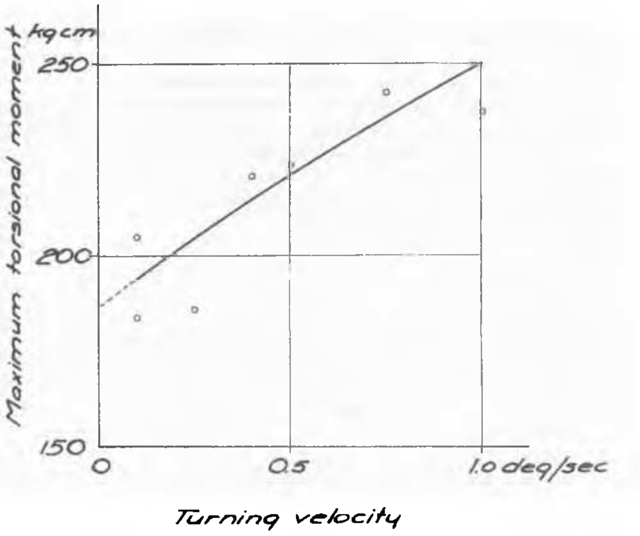
A rotating tool with two wings was driven into clay soil, and turned until the maximum forces had been registered; then the turning was stopped, and the tool withdrawn. The piece of clay in which the tool had been turned was excavated, and when it was cut at right angle to the previous direction of the axis of the rotating tool, a fairly clear surface of rupture was seen. Fig. 3 shows such a piece of excavated clay. As seen in the figure, the clay seems to have ruptured along a surface with oval, almost circular cross-section.

A piece of excavedcclay in wich the turning tool has operated.

FIG. 3

INFLUENCE OF THE TURNING VELOCITY.

In order to study the influence of the turning velocity of the lever on the maximum torsional moment, investigations have been carried out with different velocities but with the same rotating tool and in the same clay. Tests have been made at different depths, and all depths have given results similar in character. Fig. 4 shows a typical result. As seen in the figure, the maximum moment decreases, as the velocity decreases. A velocity corresponding to actual cases may now be chosen and used in the tests.



Maximum torsional moment at different turning velocities for a rotating tool with two wings.

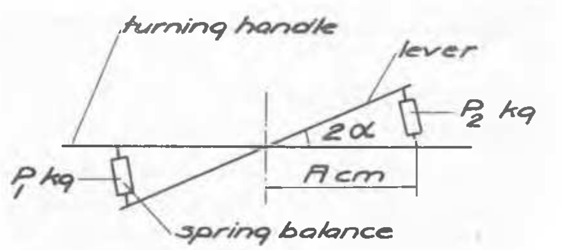
FIG. 4

In reality clay is generally loaded very slowly, so that a turning velocity approximating zero would correspond best to reality. For practical reasons howewer, it is impossible to use an infinitesimal velocity, particularly if the turning is to be done by hand. The velocity 0,1 degree per second seems in such case to be a practical lower limit, and for this reason this velocity has been chosen. In fig. 4 the maximum torsional moment at this velocity only slightly exceeds the moment obtained by extending the curve to zero. In all tests carried out up to now this difference seems to be less than 5 % of the maximum moment at the velocity of zero.

CALCULATION OF THE SHEAR STRENGTH

When loaded the spring balances extend, causing the moment arm to vary with the load. In order to calculate the real torsional moment (M) in the turning rod, a correction for the variation of the moment arm is introduced. With designations as in fig. 5 then

$$M = (P_1 + P_2) \ A \cos \alpha$$



Upper part of the apparatus.

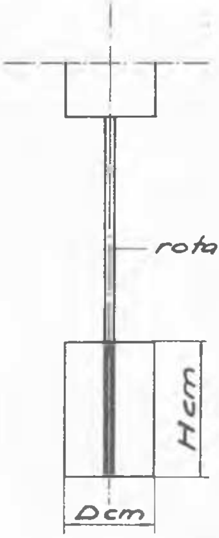
FIG. 5

The factor $\cos\alpha$, which varies with the load only, can be experimentally determined for different loads.

On the assumption,

that the surface of rupture is a circular cylinder surrounding the tool,

that at maximum torsional moment (M_{max}) the shear strength is fully developed over



Lower part of the apparatus.

FIG. 6

the whole surface of the said cylinder, including its end surfaces,

that the torsional moment, exerted by the clay upon the shaft of the rotating tool can be neglected,

and with designations as in fig. 6, then

$$M_{max} = \tau \left(\pi D H \frac{D}{2} + 2 \frac{\pi D^2}{4} \frac{2}{3} \frac{D}{2}\right)$$

$$\text{and } \tau = \frac{M_{max}}{C}$$

where C is a constant.

On account of the turning velocity, M_{max} could be 5% too high, as previously found.

According to the tests the surface of rupture is somewhat smaller than the one assumed above. Furthermore, the shear strength is surely not fully developed in both end surfaces.

The influence of these factors may well counterbalance the increase of M_{max} caused by the turning velocity.

As, further, torsional moment exerted by the clay upon the shaft of the rotating tool, is very small, and friction in the apparatus, according to several tests, is also slight, τ calculated as above may not be impaired by errors of importance.

COMPARISON BETWEEN VALUES OF THE SHEAR STRENGTH OBTAINED BY THE ROTATING AUGER, BY CALCULATIONS FROM SLIDES AND BY LABORATORY INVESTIGATIONS ON EXTRACTED SAMPLES.

The rotating auger has been used in several localities. Among them are two sites where slides had taken place, and where extensive investigations were carried out. At these investigations samples were extracted by means of the Swedish piston sampler 2) and the shear strength determined by unconfined compression test and by the Swedish cone-test. 3)

Fig. 7 and 8 show results from two boreholes, viz. the shear strength according to the rotating auger and according to the laboratory methods. In the figures the shear strength according to calculations from the slides is also represented. The calculated values are approximate and obtained by the circular arc method. In the figures some soil data is also given.

From the figures it follows:

At shallow depths under the soil surface the shear strength, according to the rotating auger, roughly equals the shear strength determined by these laboratory methods;

at greater depths the shear strength, according to the rotating auger, exceeds laboratory values considerably;

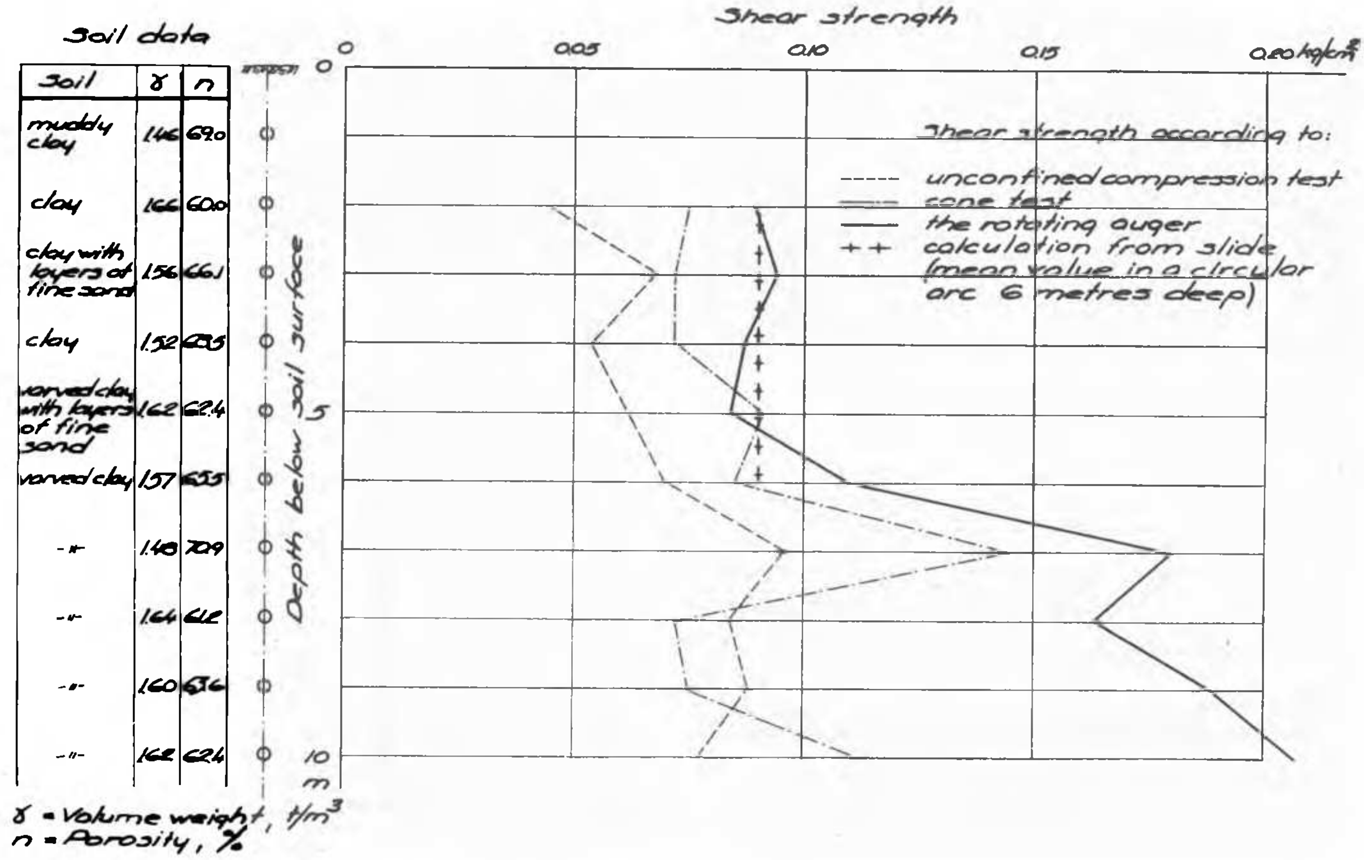
the shear strength, according to the rotating auger, seems to correspond with the strength calculated from slides, while the laboratory values are too small.

CONCLUSIONS.

The experiments carried out up to now are only few, but as all results are similar in character, the following conclusions might be drawn:

When a tool, like the one used, is turned in clay, a surface of rupture is formed with oval, almost circular cross-section.

The maximum torsional moment is influ-



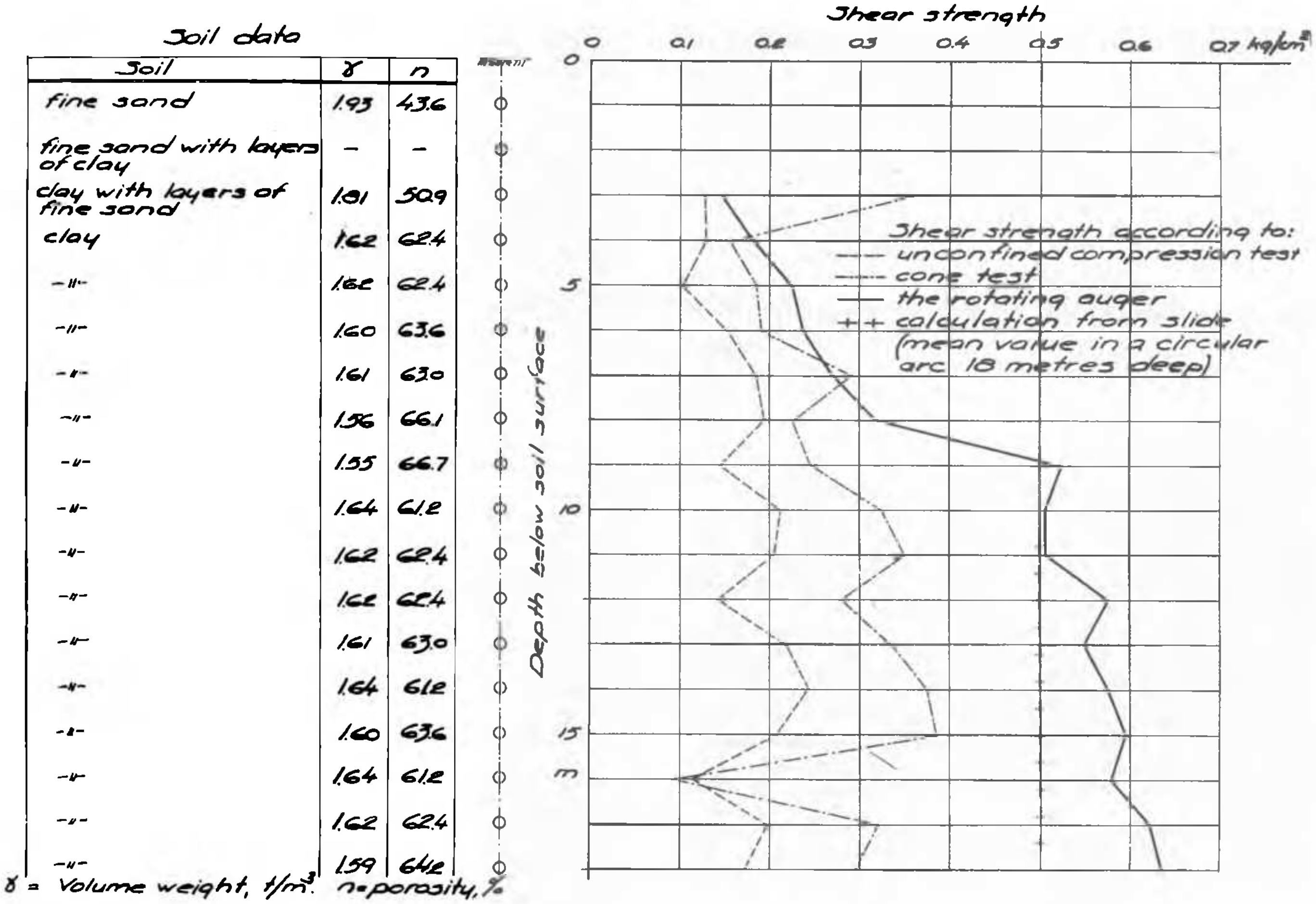
Soil data

Soil	γ	n
muddy clay	1.46	69.0
clay	1.66	60.0
clay with layers of fine sand	1.56	66.1
clay	1.52	63.5
varved clay with layers of fine sand	1.62	62.4
varved clay	1.57	65.5
-"-	1.48	70.9
-"-	1.64	61.2
-"-	1.60	63.6
-"-	1.62	62.4

γ = Volume weight, t/m³
n = Porosity, %

The shear strength determined by different methods.

FIG. 7



Soil data

Soil	γ	n
fine sand	1.93	43.6
fine sand with layers of clay	–	–
clay with layers of fine sand	1.81	50.9
clay	1.62	62.4
-"-	1.62	62.4
-"-	1.60	63.6
-"-	1.61	63.0
-"-	1.56	66.1
-"-	1.55	66.7
-"-	1.64	61.2
-"-	1.62	62.4
-"-	1.62	62.4
-"-	1.61	63.0
-"-	1.64	61.2
-"-	1.60	63.6
-"-	1.64	61.2
-"-	1.62	62.4
-"-	1.59	64.2

γ = Volume weight, t/m³. n = porosity, %

The shear strength determined by different methods

FIG. 8

enced by the turning velocity, and in such a way, that the moment decreases, as the velocity decreases.

At the velocity chosen (o.1 deg/sec)the maximum torsional moment seems to exceed by less than 5 % the value obtained by extracting the moment-velocity curve to zero.

At shallow depths under the soil surface the shear strength according to the rotating auger roughly equals the shear strength determined by laboratory methods.

At greater depths the shear strength according to the rotating auger exceeds the laboratory values considerably.

The shear strength according to the rotating auger seems to correspond with the strength calculated from slides, while the laboratory values are too small.

Or in other words, the method used to be a simple, quickly working method for determining the real shear strength of a clay soil.

SUMMARY.

The shear strength of clay is usually determined in the laboratory from samples taken from different depths of the ground. In Sweden the investigation is generally carried out by means of unconfined compression test or cone test. Usually the shear strength thus obtained increases only slightly with the depth under the surface of the ground. It is often smaller than the real strength, calculated from slides that have occurred in the same soil. This discrepancy may depend partly on disturbance of the sample caused by the sampler, partly on changes in the sample due to the decrease of pressure when the sample is extracted. These sources of error can never be entirely eliminated when the investigation is carried out on extracted samples.

On account of this a method for determining the shear strength of soil directly in the ground has been developed at The Royal Swedish Geotechnical Institute. According to this method a tool is first driven into the ground and then turned, the resistance against turning being measured. The shear strength is then calculed from the maximum resistance. The tool is shaped in such a way that, when being driven down, it disturbes as little as possible the soil to be tested, and, when being turned, it produces in the soil a surface of rupture of well defined shape. The tool is lengthened upwards by an extension rod, surrounded by a casing-pipe.

At shallow depths under the soil surface the shear strength determined by this in situ method roughly equals the strength determined by the laboratory methods. But at greater depths the former exceeds the latter considerably. The in situ values also seem to correspond with those calculated from slides, while the laboratory values are too small.

The experiments are still in an early stage, but the method, as now can be judged, seems full of promise.

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III b 4 A PRACTICAL METHOD OF RAPID MEASUREMENT OF SOIL MOISTURE AND ITS APPLICATIONS

KANO HOSHINO

Japan

I. THE METHODS USED BEFORE AND NEW METHOD.

It is essential to measure the content of soil moisture in the course of research or practise on soil mechanics. The oven-dry method has been used, but it takes at least a day or more before we can know results.

A few methods have been proposed for rapid measurement of soil moisture; for example, a method of measuring the electric resistance of soil sample and of measuring the temparature rise by mixing sulphric acid with it, but none of which has been in common use because of the requirement of special instruments or because of the difficulty or inaccuracy of the process.

A new method of rapid measurement of soil moisture based on a physical principle can afford results in about ten minutes with ample accuracy for engineering purposes.

Principle of the method is very simple as well known, and is based on the fact that the net specific volume or the net volume per unit weight of a sample excluding air void changes in linear proportion to the percentage in weight of moisture to the total soil sample.

A practical procedure was devised by author for measuring the net specific volume of soil sample, which is to be called the index of moisture.

Equipments required for this method are not special made, but we can find them all on the shelf in our laboratory, such as flask, funnel, beaker, glass tube and balance, etc.

It is very easy to exercise this method both in laboratory and in field, and we can know results at once.

If the apparent specific density of soil is known, the index of dry density can be determined, which proportionates in linear relation with the dry density. In this case, the saturation curve can be drawn in the simplest form with no relation to the specific gravity of soil particles.

A number of results have been obtained successfully by this method both in laboratory and in field, especially in the field of compacting soil to obtain the maximum density at optimum moisture. Some examples of the results observed are reported in this paper.

II. PRINCIPLE AND PRACTICE OF NEW METHOD.

Let the specific gravity of soil particles be equal to 2.50 and that of water to 1.00, then the value of net specific volume of perfect dry soil sample is 0.4 and that of water is 1.0, and the corresponding percentages of moisture content are zero and 100 respectively. In the case of mixing both in equal weight, it amounts to 0.7, corresponding to 50 percent of moisture content. We can know that the net specific volume of a soil sample has a linear relation to the percentage of moisture content to the total weight of sample. In general, if we use the following designations,

Gs=specific gravity of soil particles
W=weight of a soil sample
V=net volume of the soil sample, excluding air void
Ww, Ws=weights of water and soil particles contained in the soil sample
w=percentage of soil moisture to the total weight of the sample
Ω=net specific volume of the sample (index of moisture)
Ga, Gd=apparent specific gravity and dry density of the sample
Γ=index of dry density

then we get the following relations

$$w = Ww/W \times 100 \text{ and } \Omega = V/W = Ww/W + (W-Ww)/GsW \qquad (1)$$

Therefore

$$w = (\Omega - 1/Gs)/(1-1/Gs) \times 100 \qquad (2)$$

We know from (2) that the moisture content w is in linear relation to the net specific volume Ω, which is to be called the index of moisture.

If the apparent density of soil sample is known, the index of dry density can be defined by

$$\Gamma = (1-\Omega)\,Ga \cdots\cdots \qquad (3)$$

hence

$$\begin{aligned} Gd &= (1-w/100)Ga \\ &= \Gamma/(1-1/Gs) \end{aligned} \qquad (4)$$

We can know that the dry density is in linear proportion to the index of dry density.

In the case of saturating the voids of a soil sample by water (no air void), the moisture content and the dry density stand in a relation of

$$w = 100(1-Gd/Gs)/(1+Gd-Gd/Gs) \qquad (5)$$

which gives the different saturation curve with the different value of Gs. Using the both indexes Ω and Γ in the new method, we can express the saturation curve by

$$\Gamma = 1/\Omega - 1 \cdots\cdots \qquad (6)$$

which has a simplest form easy to remember.

The equipments to be prepared for this method are as follows (Photo. 1):

Quantity	Unit	Equipment
1	each	glass flask, 4001 ltr., slender necked
1	"	glass funnel, 45 mm dia., with a sharp point
2	"	glass beakers, 100 c.c. and 500 c.c.