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Reproducibility of Borehole Shear Test Results in Marine Clay

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ABSTRACT: An investigation was conducted to determine the variability of borehole shear test results obtained in testing soft and medium consistency marine clays. A statistical comparison of the results of stage tests obtained by different operators at two test depths at a research site is made. An additional comparison of the results obtained from stage tests and fresh shearing and a brief discussion of the linearity of both types of tests is also made. A short summary discussing the applicability of the results is also presented.

KEY WORDS: borehole shear test, precision, soil testing, clays, shear strength

The use of the borehole shear test (BST) for in-situ measurement of shear strength in soils appears to be gaining popularity in recent years among practicing geotechnical engineers. While certain aspects of the test are still open to debate, particularly regarding effects of borehole disturbance, drainage conditions, proper shear rates, and so forth, the equipment has for the most part proven to be rugged, versatile, and efficient to use. As with all soil tests, however, there is always some uncertainty as to the reliability of results, particularly when only a few tests are conducted at a site. In particular, the reproducibility of the test results in any given soil type may include some effect of the test equipment and procedure used and the experience of the operator, especially if more than one operator is used on a project.

The BST has been described in detail by a number of investigators [*1–5*] and will only be reviewed briefly here. Ideally, the philosophy of the test is to perform a shear test in situ on the sides of a borehole in order to obtain independent measurements of soil friction and cohesion. In order to accomplish this, an expandable shear head equipped with diametrically opposed serrated plates is lowered into a borehole. A constant normal force is then applied to the plates via compressed gas, causing the plates to contact the sides of the borehole. In order to initiate a soil shear failure, the shear head is pulled vertically until a peak shear force is recorded. The test instrument is shown in Fig. 1. Essentially, two types of tests may be conducted: (1) stage tests in which the normal stress is increased incrementally after each peak shear force has been recorded without relocating the shear head and (2) fresh shearing in which the shear head is retracted and removed after the peak shear force is recorded so that the shear plates may be cleaned and a new shearing surface is tested.

There have been some criticisms regarding the use of the BST in certain types of soils (for example, Ref *6*), however a discussion of the application of the test is beyond the scope of this paper. Even so, it is of interest to have an understanding regarding the precision of the obtained results from any soil test. The purpose of this paper is to describe work that was undertaken to assess the reproducibility of BST results and in particular investigate operator variability.

Precision of Soil Tests and Sources of Error

It is often assumed that soil tests give exact values of a desired property, however this is not true, since the test results usually contain errors. For real soils, large errors may derive from a number of sources [*7*]. Errors that could affect the precision of test results obtained from in-situ tests, such as the BST may include:

1. *Natural Soil Variability*—The testing of soils that are inherently nonuniform will automatically produce results that are variable, all other factors being minimized.
2. *Equipment Variability*—The use of nonstandard equipment or test procedures should be discouraged. Additionally, calibration errors resulting from excessive use or wear may be introduced.
3. *Operator Variability*—Tests that require extensive operator experience or are simply too complex should be avoided for routine work.
4. *Data Interpretation Variability*—Tests that require extensive interpretation of results to obtain a final value may cause errors.

Ideally, test techniques that minimize the latter three sources of error would be desired.

Considering the BST, potential errors may be minimized if certain precautions are used:

1. If a standardized test procedure is used to conduct tests and only one apparatus with known calibration constants is used, error from the machine effect may be reduced.
2. Errors from data interpretation may be eliminated by using least square linear regression analyses to reduce data.

Therefore if these steps are taken, it may be assumed that any variability in results would be due solely to natural variability of the soil being tested and operator variability. If it can be established that

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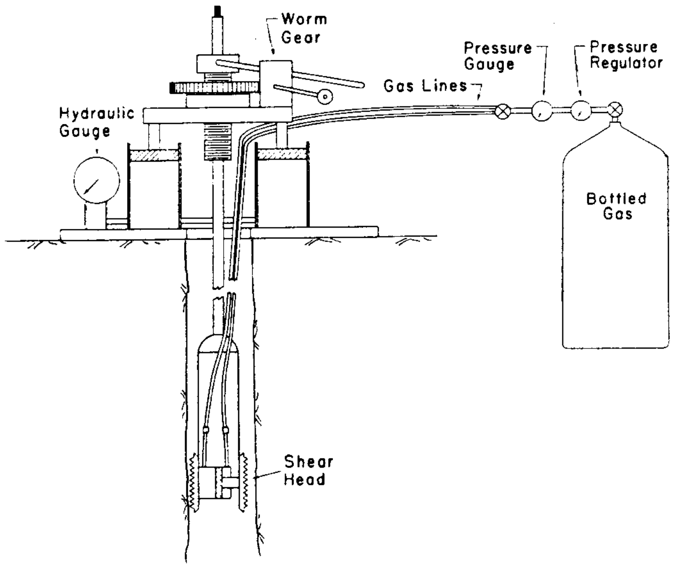

FIG. 1—*Borehole shear test.*

if the test is relatively simple to conduct, then operator variability may be nonexistent or at least insignificant.

One way to look at the variability of a measured soil property is to use the standard deviation of a population as a measure of the error, such that

$$\sigma_p^2 = \sigma_t^2 + \sigma_s^2 \quad (1)$$

where

σ_p = standard deviation of the property being measured (that is, the test result),
σ_t = standard deviation deriving from the test method, and
σ_s = standard deviation deriving from the soil variability.

Note: σ_t and σ_s are independent. Thus, for a perfectly uniform soil in which $\sigma_s = 0$, the variability of the measured property would be attributed entirely to errors in the test. Likewise if $\sigma_t = 0$, then σ_p is totally attributed to inherent soil variability. In the case that $\sigma_s \gg \sigma_t$, σ_p will reflect the spatial variability of the soil, and similar results would be obtained from either an experienced or inexperienced operator.

The variability of the test procedure is the sum of machine and operator error

$$\sigma_t^2 = \sigma_m^2 + \sigma_o^2 \quad (2)$$

where

σ_m = standard deviation from the machine and
σ_o = standard deviation from the operator.

Note: σ_m and σ_o are independent. Obviously, it becomes a formidable task to quantify the contribution from each of the sources of error for any particular test.

An alternative approach to test result variability may be to use the dimensionless coefficient of variation (CV), defined as the ratio of the standard deviation to the mean. However the coefficient of variation is sensitive to the mean and therefore should only be used when two populations have about the same mean. For example, two populations with the same standard deviation but different means would give different coefficients of variation, in which case the standard deviation might be a better indicator of variability.

Testing Program

Tests were performed at a research site in Massena, NY, located near the St. Lawrence River. In this area, late Pleistocene marine clay deposits occur in low areas on the landscape. These materials are considered moderately sensitive clays and typically consist of an overconsolidated crust overlying normally consolidated materials. The site was chosen since it was felt that the soils would be fairly uniform and therefore it was hoped that soil variability might be reduced. General geotechnical characteristics of the marine clay deposits around the Massena area have been described elsewhere [*8,9*]. An initial test boring was performed at the site before the start of the BST program in order to obtain specific site stratigraphy and general soil properties. A generalized soil profile of the site is shown in Fig. 2. At the time of the work the depth to the perched water table was noted at about 2.4 m (8 ft).

All BSTs were performed using conventional 50.8- by 63.5-mm (2.0- by 2.5-in.) shear plates with twenty-five 60° apex teeth as supplied by the manufacturer. A consolidation time of 5 min was used for all test points. The applied normal stress was in the range of 0 to 176 kPa (0 to 25 psi). For all tests, five data points were obtained for each failure envelope. However, in the analysis of the stage tests, the first data point was eliminated from the regression analysis of each test since this initial point is a fresh shear data point and does not present stage testing. Least squares linear regressions were used to determine ϕ and c for all tests. Moisture samples were obtained at all test locations. Samples were sealed in moisture tins and transported to the laboratory for oven drying. Boreholes were drilled with a bucket-type hand auger.

Results

In order to investigate operator variability, two operators each performed 24 tests at a depth of 1.5 and 3.0 m (5 and 10 ft). Therefore one test series was conducted above the water table, and one test series below. Operator A had several years experience with the BST, while Operator B had no prior BST experience and was only given brief instructions. In order to reduce spatial soil variability and provide a uniform sampling pattern, a grid of boreholes was layed out before testing with the nominal distance between boreholes equal to 0.76 m (2.5 ft). Operators were used at random to perform tests. As noted in Fig. 2, a change in soil conditions occurs at about 2.6 m (9 ft), therefore the two test series were performed on slightly different soils.

Histograms of moisture content determinations for all test locations are shown in Fig. 3 for both test depths. These results indicate a substantial difference in moisture content between the upper and lower test locations, which would tend to substantiate the assumption that a change in soil occurred and therefore two different populations were being investigated. The upper test location gave a mean moisture content of 36.4% with a standard deviation of 3.4%, whereas the mean and standard deviation for the lower test depth were 59.3 and 5.0%, respectively. A summary of test results obtained by both operators is presented in Table 1. The coefficient of variation for both ϕ and c is generally within the limits displayed by laboratory testing [10].

Operator Variability

Mean Values

It is of interest to compare mean values of ϕ and c obtained by both operators for tests conducted at each depth. This may be done by testing the null hypothesis $H_o: \mu_A = \mu_B$ where μ = true population mean. A suitable test criterion is the t-test, which may be stated as

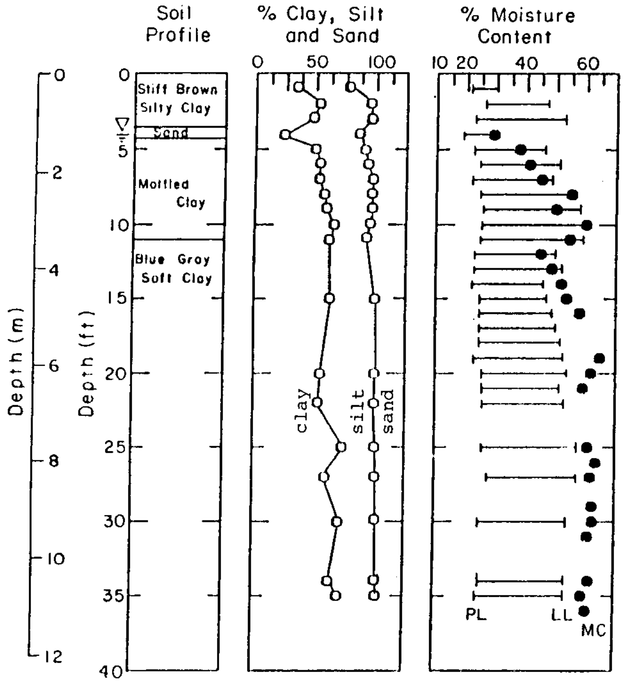

FIG. 2—*Geotechnical profile, Massena test site.*

$$t' = \frac{\bar{X}_A - \bar{X}_B}{\sqrt{\frac{\sigma_A^2}{N_A} + \frac{\sigma_B^2}{N_B}}} \tag{3}$$

where

$\bar{X}$ = sample mean,
σ = sample standard deviation, and
N = sample size.

The value of t' obtained aboved may be compared to a standard t statistic for $2N - 2$ degrees of freedom, in this case 46. These comparisons are shown in Table 2. As noted, in all cases the values of t' are less than the t statistic given for the 0.5% significance level. Therefore, it may tentatively be concluded that mean values of friction angle and cohesion obtained by both opertaors are not significantly different.

Variance

While the conclusion that the mean values of ϕ and c are not significantly different is important from a design standpoint, it is equally important to determine how the data from each sample set are distributed about the individual means. That is, if we wish to make inferrences regarding the variability of the population of each operator, a comparison of the variances of each population is necessary. This may be accomplished by using the F-test with the null hypothesis stated as $H_o: \sigma_A^2 = \sigma_B^2$. The F statistic may be calculated as

$$F = \sigma_A^2/\sigma_B^2 \tag{4}$$

where σ^2 = variance. These comparisons are shown in Table 3. When compared with the F statistic for 23 degrees of freedom, it is

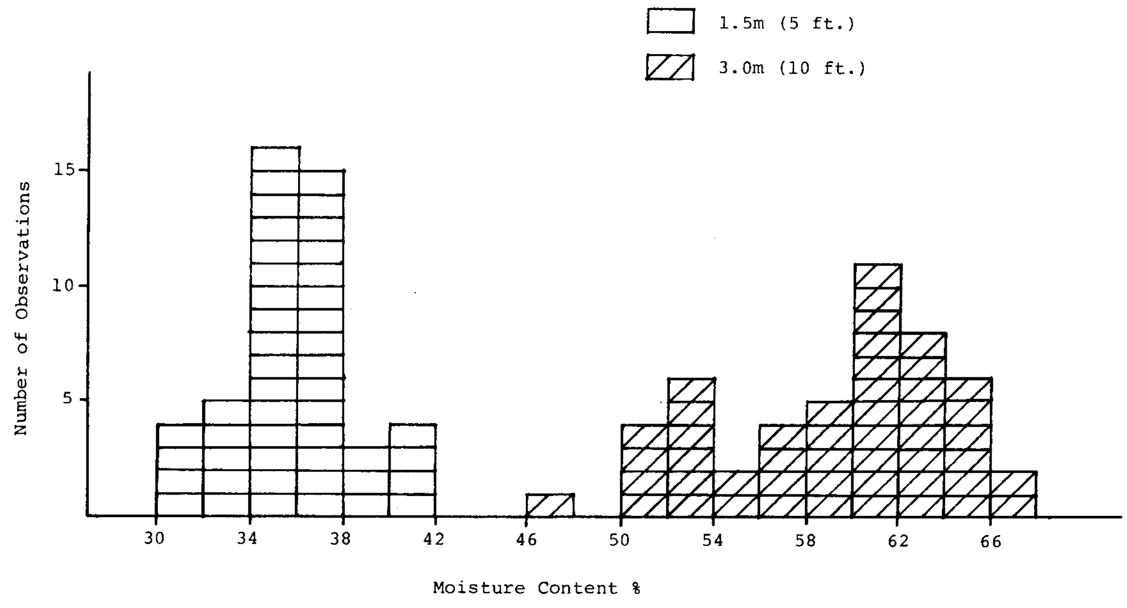

FIG. 3—*Histograms of moisture content for both test depths.*

TABLE 1—*Summary of BST results from two operators.*

Operator		ϕ, Degrees	c, kPa
	DEPTH = 1.5 M (5 FT)		
A	range	19.9 to 34.3	0.8 to 29.7
	$\bar{X}$	25.4	18.7
	σ	3.2	6.4
	CV, %	12.5	34.3
B	range	21.4 to 29.8	1.4 to 31.8
	$\bar{X}$	25.4	19.3
	σ	2.3	6.4
	CV, %	9.1	33.2
Combined	$\bar{X}$	25.4	19.0
	σ	2.8	6.4
	CV, %	11.0	33.7
	DEPTH = 3.0 M (10 FT)		
A	range	20.8 to 26.6	1.1 to 10.4
	$\bar{X}$	23.9	5.4
	σ	1.2	2.5
	CV, %	5.0	46.3
B	range	20.2 to 26.5	0.0 to 13.1
	$\bar{X}$	24.1	6.1
	σ	1.8	3.3
	CV, %	7.5	54.1
Combined	$\bar{X}$	24.0	5.7
	σ	1.8	2.4
	CV, %	7.5	42.1

TABLE 2—t-*test for comparison of mean values (null hypothesis* $H_o: \mu_A = \mu_B$*).*

	t'		
Depth, m	ϕ	c	$t_{46,0.005}$
1.5	0.026	0.323	2.722
3.0	0.326	0.765	2.722

TABLE 3—F-*test for comparison of variances (null hypothesis* $H_o: \sigma_A^2 = \sigma_B^2$*).*

	F		
Depth, m	ϕ	c	$F_{23,23,0.01}$
1.5	1.900	1.005	2.74
3.0	1.137	1.778	2.74

seen that the data are significant at the 1% level. Thus, it may be concluded that there is no significant difference in the variances displayed by Operators A and B, and therefore both operators provide the same reproducibility.

Comparisons of the mean values and the variances and thus the use of the t and F tests assume that the populations are both normally distributed. Histograms of ϕ and c for each test depth are shown in Fig. 4 and as shown, the data appear to reasonably approximate normal distributions. This is also substantiated by the χ^2 test at the 10% level.

Based on the results of the t-test and the F-test, it might now be appropriate to combine the results of Populations A and B and describe the shear strength at each test depth with an individual statistic for both ϕ and c. These values are indicated in Table 1. While the friction angle values from the two test depths are not significantly different, the cohesion is considerably larger for the shallower tests. This is to be expected since the clay at this depth is highly overconsolidated. Using the combined results for each depth, it would now be possible to define confidence limits about each of the combined mean values of ϕ and c from Table 1 for use in design.

A preliminary attempt was made to investigate the ability of different operators to provide meaningful BST results. After only brief instructions, ten operators with only limited experience in geotechnical engineering were asked to conduct a stage BST at a depth of 1.5 m (5 ft) in ten adjacent boreholes at the same site as all other tests. By using different operators, it was hoped that a "worst condition" situation would be created to simulate the possibility of having a number of technicians at a site performing the same test. In this way, the error caused by the "operator effect" would hopefully be maximized. The results are presented in Table 4. These results compare very well with the results given in Table 1. In fact, only 2 of the 10 values of ϕ from Table 4 are outside of the 95% confidence interval for ϕ, while only one value of c is outside the 95% confidence interval for c. These results indicate that with only a minimal amount of expertise, reasonable results may be obtained by inexperienced technicians.

If it is desired to make an initial determination of the number of tests N required to bring the mean values of ϕ and c within acceptable design limits, we may apply the t-statistic and calculate N as [*11*]

$$N = \frac{t\sigma}{\chi\bar{X}} \quad (5)$$

where

t = t-statistic for $P = 95\%$,
σ = sample standard deviation,
$\bar{X}$ = sample mean, and
χ = allowable error in $X = 10\%$.

Using the data from Table 4 for $\bar{X}$ and σ and solving Eq 5 for N, we may determine that while only five tests are required to estimate the mean ϕ within 10%, 23 tests would be necessary to give the same accuracy on mean cohesion.

Stage Testing Versus Fresh Shearing

For some time, a concern has been expressed about the technique of stage testing and the applicability to different soil types (for example, Ref *4*). Additionally, it might be thought that stage testing produces more linear results than fresh shearing because there is less chance to introduce soil variability. It was decided to investigate the difference between stage test results and fresh shear test results at the same test depth. Four different operators conducted four fresh shear tests each at a depth of 1.5 m (5 ft) adjacent to the location of the grid system previously described. Test results are summarized in Table 5. If the error arising from the variability of each operator is neglected, and the results are combined, a comparison may be made between these data and the combined results previously obtained from stage tests summarized in Table 1. Once again using the t test and the F test, the results indicate that at the

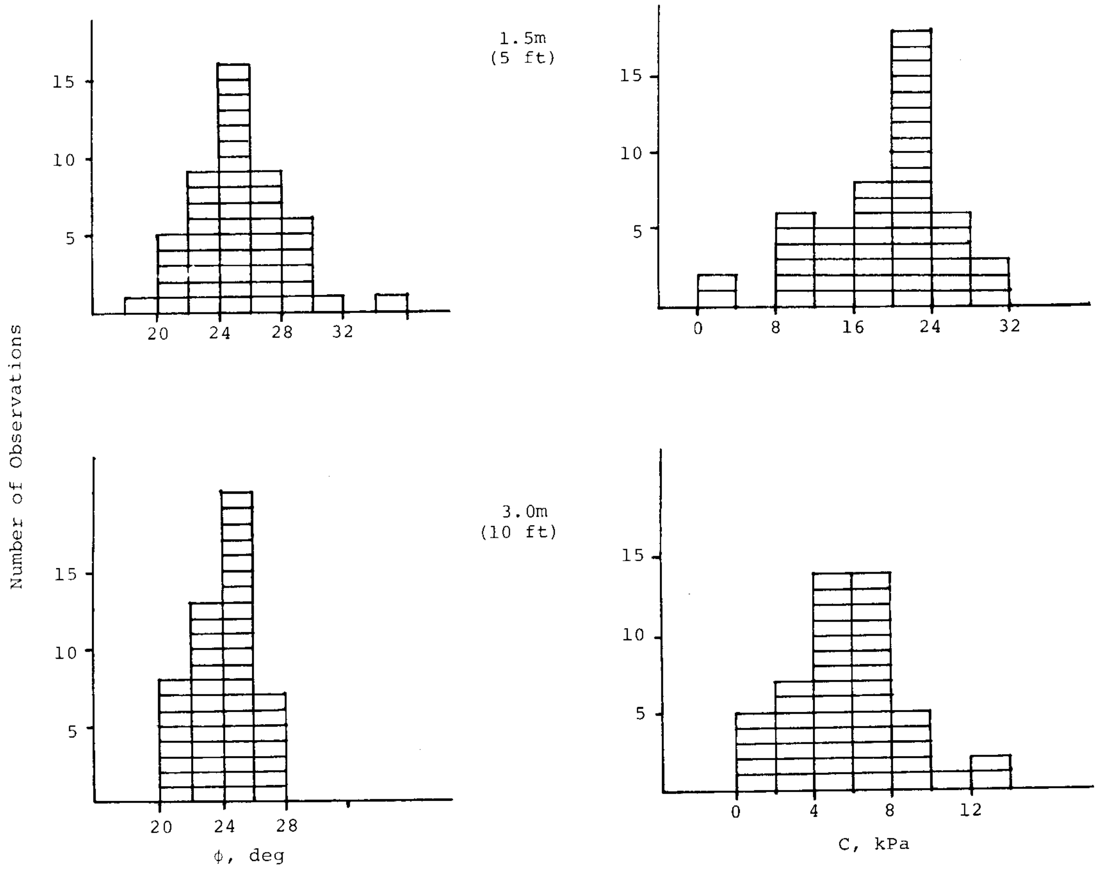

FIG. 4—*Histograms of friction angle and cohesion for both test depths.*

TABLE 4—*BST results from inexperienced technicians (depth = 1.5 m [5 ft]).*

Location	Operator	Friction Angle, Degrees	Cohesion, kPa	r^2	Moisture, %
AA1	A	24.4	27.0	0.9968	36.2
AA2	B	25.5	20.1	0.9984	34.4
AA3	C	24.4	17.3	0.9474	35.3
AA4	D	26.9	14.5	0.9907	34.8
AA5	E	21.7	23.6	0.9771	34.4
AA6	F	23.1	17.7	0.9933	31.7
AA7	G	25.5	19.3	0.9848	31.9
AA8	H	24.8	22.1	0.9957	38.3
AA9	I	20.7	15.2	0.9868	39.9
AA10	J	27.2	15.7	0.9993	30.4
Mean		24.4	19.3		34.7
Standard deviation		2.09	4.0		2.9
Coefficient of variation, %		3.6	20.8		8.5

5% level there is no significant difference between the results from stage tests and fresh shear tests.

The linearity of individual tests may be obtained from the value of the correlation coefficient of least square linear regression r^2. A comparison of the mean values of r^2 from the 48 stage tests and 16 fresh shear tests indicates that while the fresh shear gives a slightly lower value, for the degree of precision required for most design situations, there is essentially no difference in results, 0.9940 and 0.9674, respectively.

Conclusions

A number of general conclusions may be made regarding the results of the testing program described:

1. Results of borehole shear tests conducted on a marine clay at two different depths at a test site indicated that statistically there was no difference in the mean and variance of either friction angle or cohesion between an experienced operator and an inexperienced operator.

TABLE 5—*Summary of fresh shear BST.*

Operator	Test	ϕ, Deg	c, kPa	r^2	M, %	Mean ϕ	Mean c	Standard Deviation ϕ	Standard Deviation c	CV, % ϕ	CV, % c
A	1	25.5	18.8	0.9914	38.5						
	2	25.8	22.5	0.9959	40.3						
	3	21.6	27.0	0.9590	38.2	24.6	22.8	2.0	3.4	8.1	14.9
	4	25.4	22.8	0.9966	42.3						
B	1	21.5	29.3	0.9058	37.3						
	2	30.2	8.4	0.9931	37.7						
	3	29.7	8.8	0.9834	37.8	26.6	15.7	4.1	9.8	15.4	62.4
	4	24.9	16.2	0.9846	40.9						
C	1	25.6	13.7	0.8589	40.3						
	2	24.0	23.7	0.9600	38.8						
	3	20.9	19.3	0.9865	...	22.8	18.5	2.3	4.2	10.1	22.7
	4	20.8	17.3	0.9520	...						
D	1	28.1	24.6	0.9816	38.9						
	2	19.8	30.4	0.9728	37.9						
	3	26.0	13.9	0.9635	...	25.1	22.4	3.6	6.9	14.3	30.8
	4	26.4	20.5	0.9935	...						
Combined											
Mean	24.8	19.8									
σ	3.2	6.6									
CV, %	12.9	33.3									

2. The variability of the combined results of both operators, as described by the coefficient of variation, was higher for cohesion than for friction angle, which is generally as expected. The coefficient of variation for cohesion was 33.7 and 42.1% for two test depths, and for friction angle was only 11.0 and 7.5%.

3. Test results obtained by ten inexperienced technicians generally fell within the 95% confidence limits and indicate that the test is simple to perform.

4. A comparison of the results obtained from stage tests and fresh tests conducted at the same depth indicates that there was no significant difference in mean and variance of friction angle and cohesion for the clay tested.

5. A comparison of the linear regressions obtained from individual stage and fresh tests indicates that there was no significant difference. The linearity of both types of tests was excellent, with the regression coefficient r^2 generally greater than 0.95.

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