	Wiener Tegel		Little Belt Clay	
Ring Shearing Apparatus with Fixed Rings	Natural Consolidation	Over-Consolidation	Natural Consolidation	Over-Consolidation
$k = \tau_2/\tau_a$ (before failure)	1.06-1.07	1.07-1.11	1.07-1.08	1.08-1.09
$k' = \max\ \tau_2/\max\ \tau_a$	1.02-1.03	1.00-1.01	1.02-1.03	1.00-1.01
$k'' = \min\ \tau_2/\min\ \tau_a$	- 0.92 -	- 1.00 -	- 1.00 -	-1.00 -
s max) First test	100%	100%	100%	100%
s min)	71-74	75-80	39-40	39-41
s' max) After several tests) and a rest period	107-110	109-111	45-50	- 42 -
s' min) of five days	82-90	82-85	- 40 -	- 34 -
Terzaghi Shearing Box				
s max) First test	96	110	101	112
s min)	80-84	95-98	70-75	80-85

As will be seen from this table, the maximum and minimum values of τ_2 are nearly identical with those of τ_a, except where a temporary minimum is concerned as for Wiener Tegel. As such a temporary minimum is primarily of theoretical interest, it suffices in most practical cases to determine τ_a. In comparison with the Krey-Terzaghi apparatus, the ring shearing apparatus furnishes nearly the same values for s_{max} in case of natural consolidation of the sample, but 10 to 12% lower values in case of strong overconsolidation. Probable causes for this difference have already been mentioned, but the case should be further investigated. Especially to be noted are the large decreases of shearing resistance after failure and the large differences in these minimum values of the shearing resistance, as determined by the two types of apparatus. The cause of these differences is that the minimum values of the shearing resistance cannot be reached during the limited horizontal movement of the Krey or similar types of apparatus.

Conclusion. The ring shearing apparatus is primarily suited for the testing of remoulded soils and is especially adapted for the investigation of the plastic flow before and after failure and of the temporary or permanent decrease of the shearing resistance after failure. Tests with remoulded samples of two soils, approximately representing the upper and lower limit of the true clays, show that the decrease in shearing resistance after failure depends to a large extent on the displacement after failure and may be as large as 30%, respectively 66% of the original maximum value of the shearing resistance. Furthermore, by bringing the plastic flow to a nearly a full stop, a rapid and complete recovery of the shearing resistance takes place in case of the silty clay, while this recovery by the fine plastic clay is very slow and probably also incomplete.

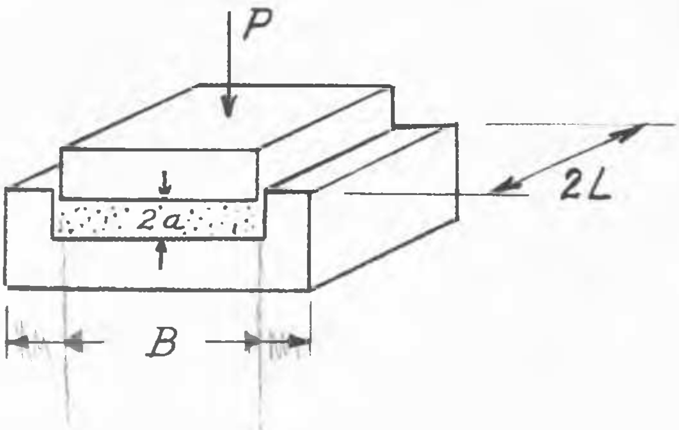
The tests were made under the supervision of Professor Terzaghi. The ring shearing apparatus used in this investigation, was designed by the author.

AN INVESTIGATION OF JÜRGENSON'S SQUEEZE-TEST

No. D-12 Arpad Warlam, S.M., former student at Graduate School of Engineering, Harvard University; now Instructor at the Technical University of Budapest, Hungary

Symbols.

P = total load on sample
s = shearing stress
2a = thickness of sample
B = width of sample along open faces
2L = length of sample along closed side walls



Reference. Jürgenson, The Shearing Resistance of Soils. Journal Boston Society of Civil Engineers, July 1934.

Tentative Conclusions. The squeeze test can be used for determining shearing resistance of clays, provided the squeeze box is calibrated by direct shearing, or unconfined compression tests.

Calibration is necessary, because at the present no general formula is available for evaluating the test data, and tests run with boxes of different size, when computed by the existing formulae, yield different values for shearing resistance.

For computing shearing stresses (subject to modification according to the box-constant obtained by calibration) the simplest formula ($s = a \cdot P/B \cdot L^2$) derived originally by L. Jürgenson may be used, if certain precautions are observed in the construction of the squeezing box regarding its proportions. The B side must be about one and a half times larger than the 2L side. In this case it is not necessary to take side-friction into account. See Fig. 1.

Furthermore, by selecting proper dimensions for the squeezing box, the computations can be made very simple. For any squeezing box the above formula may be changed to one, where a constant c, multiplied by the normal load P and reduced thickness, h_r yields the shearing stress: $s = c \cdot P \cdot h_r$. If the constant c is made unity, the computation will consist of a single multiplication: $s = P \cdot h_r$.

Effect of size of the box on the shearing resistance computed from the $s = a \cdot P/B \cdot L^2$ formula is considerable. Tests on materials at liquid limit in small squeeze box yielded low values, in large box greater values. The difference between a 6.8 x 11.1 cm^2 box and a 10 x 15 cm^2 box was $s = 9.0$ g/cm^2 and 31.0 g/cm^2, or one to three and a half. This makes it clear experimentally, why absolute shearing resistance from the above formula cannot be computed, and why calibration is necessary. Fig. 2.

In the testing technique the most important and most difficult requirement is the quick running of the squeeze tests. The normal stresses that are relatively high especially on thin samples, cause consolidation, if sufficient time is allowed. Consolidation of any practical magnitude must be eliminated, otherwise the test cannot be evaluated. Excepting only highly impervious clays, the total testing time for causing a compression of 30% should not exceed two minutes. Failure, irrespective of the consistency of the clay samples occurs between 10% and 20% compression. Therefore it is sufficient to continue the test to 30% compression. These percentage values, however, may not be entirely the same for boxes of very different proportions, especially when comparing large boxes and thin samples, with small small boxes and thick samples.

Accurate reading of the compression-indicating-extensometer can be done only after considerable practice. Motion of the dial's hand indicates both the plastic flow, and the unavoidable consolidation. Therefore it is necessary to estimate the moment when the plastic flow under a newly imposed load practically ends, and consolidation becomes noticeable; then a quick reading must be taken, and the loading continued immediately.

Time of plastic flow of soft and stiff clays differs considerably. Soft clays reach equilibrium under a new load in 3-5 seconds, stiff clays, near plastic limit, need 10-15 seconds.

In case of very stiff clays it is impossible to wait even until the plastic flow ceases; the reading must be taken earlier.

Because of the considerable "lag of the dial", especially in case of stiff clays, automatic (continuous) loading is impossible. There is always certain phase-difference between the load and the dial. This difference amounts to about 5-15 seconds. Considering the necessary rapid loading, there is no static equilibrium during the entire test, and the simultaneously observed dial and load values do not belong together.

The squeeze box may be built satisfactorily of wood. By soaking the wood for 5-10 hours in hot paraffin before the construction of the box, any future warping is eliminated.

The clay sample must be compressed between two rough plates. Waterproof sandpaper or sandcloth attached with shellac to the roof and bottom of the box provide satisfactory rough surfaces. if carefully glued the sandpaper will prove endurable for great many tests. Using the coarsest type (No. 4) available on the market, this grit will be rough enough for testing clays in very stiff consistencies, even at the plastic limit.

There is no need for rubber and glass lining in order to eliminate side friction, if $B = 1.5 \times 2L$.

Analysis of the shearing stress-compression diagrams, Fig. 3, discloses an interesting difference between tests on remolded samples of soft and stiff clays. For soft clays the shearing resistance remains practically constant from 18 to 60 and more per cent compression. Stiff clays, about at the plastic limit, fail with a sudden break.

The failure with break of the stiffer clays, however sharp it may be on the plotted curve, cannot be seen during the test. Not even the beginning of the plastic flow can be discerned by eye, because already during the elastic compression the sides bulge out, as the clay, being saturated with water, is incompressible.

Effect of consolidation, in slower tests (5 to 10 minutes), even in case of quite impervious clays, is so great, that it may fully conceal the failure, by showing no sharp turn of the stress-strain curve.

In order to avoid consolidation, especially in case of stiff clays it is necessary to estimate the load that will cause failure; load the sample up to 80% of this weight at once, then increase the load step by step thus, that sufficient number of readings may be taken and a good curve plotted. If we cannot guess the failure load, we may load the sample rapidly, until the dial indicates 10 per cent compression. The test proper begins only after 10-12% compression, because this first region is of not much interest, and may be in the plot well approximated by a straight line.

For comparative study of strengths of different clays, or strengths of the same clay with various water contents, with the squeeze tests very accurate results can be obtained. Test points at various water contents lie on, or within one per cent near the $s = f(w)$ line, Fig. 4. This line may be determined by squeeze tests as accurately as the flow line by the liquid limit tests, and for a much wider consistency range.

Acknowledgement. This investigation was suggested by Professor A. Casagrande to whom the author is also

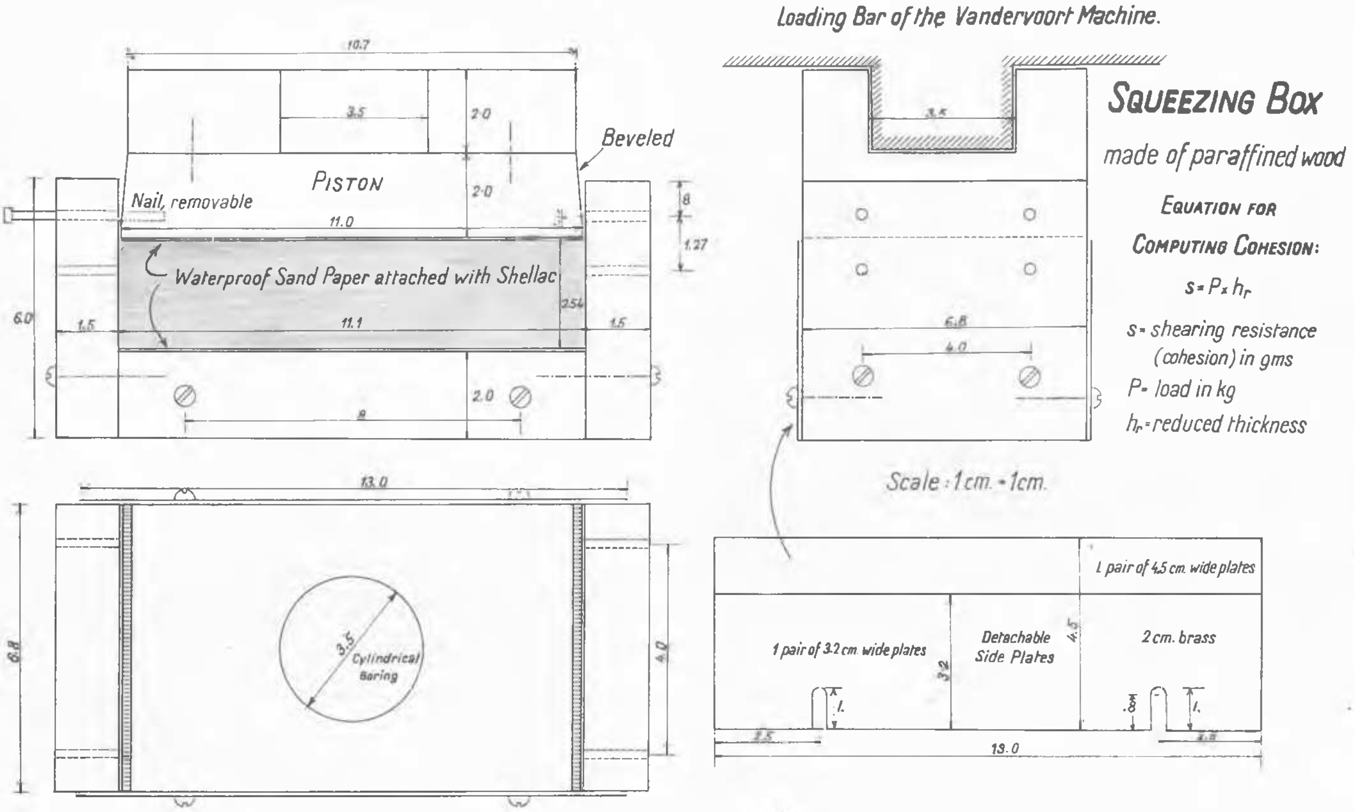


FIG. 1

2-7-36 A. WARLAM

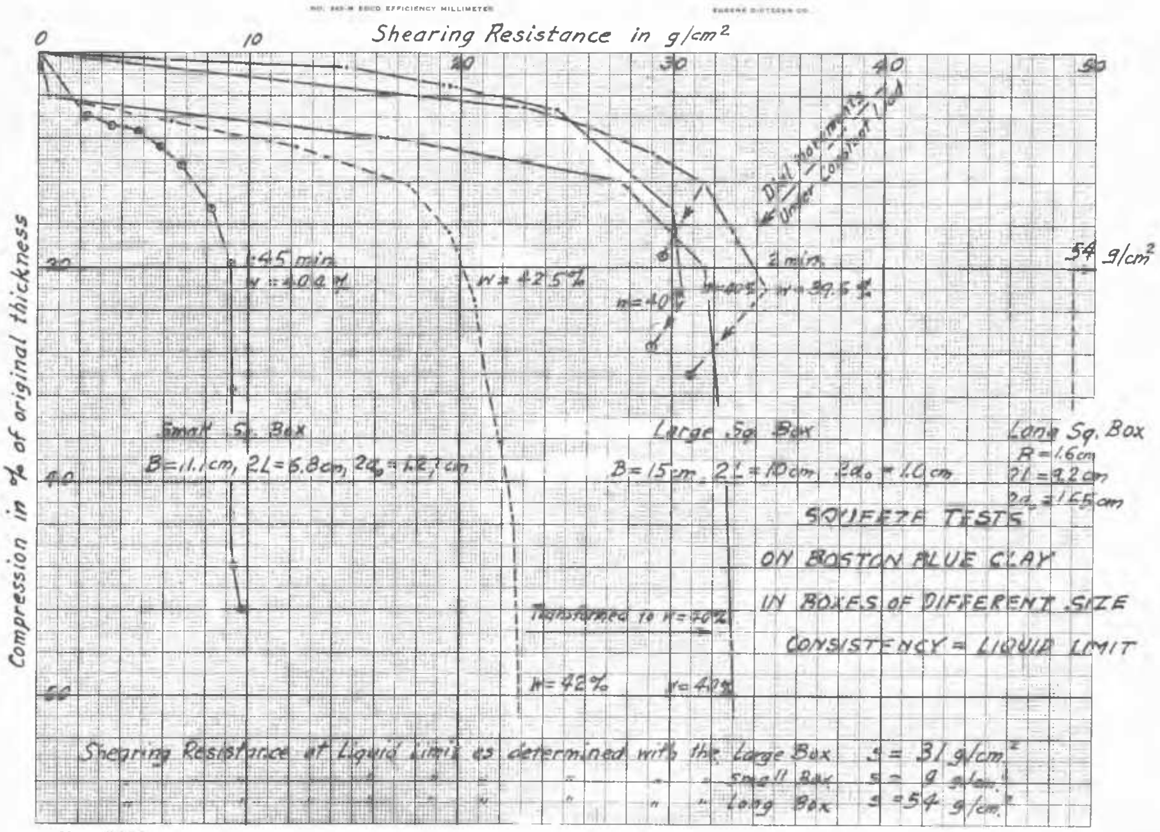


Fig. 2

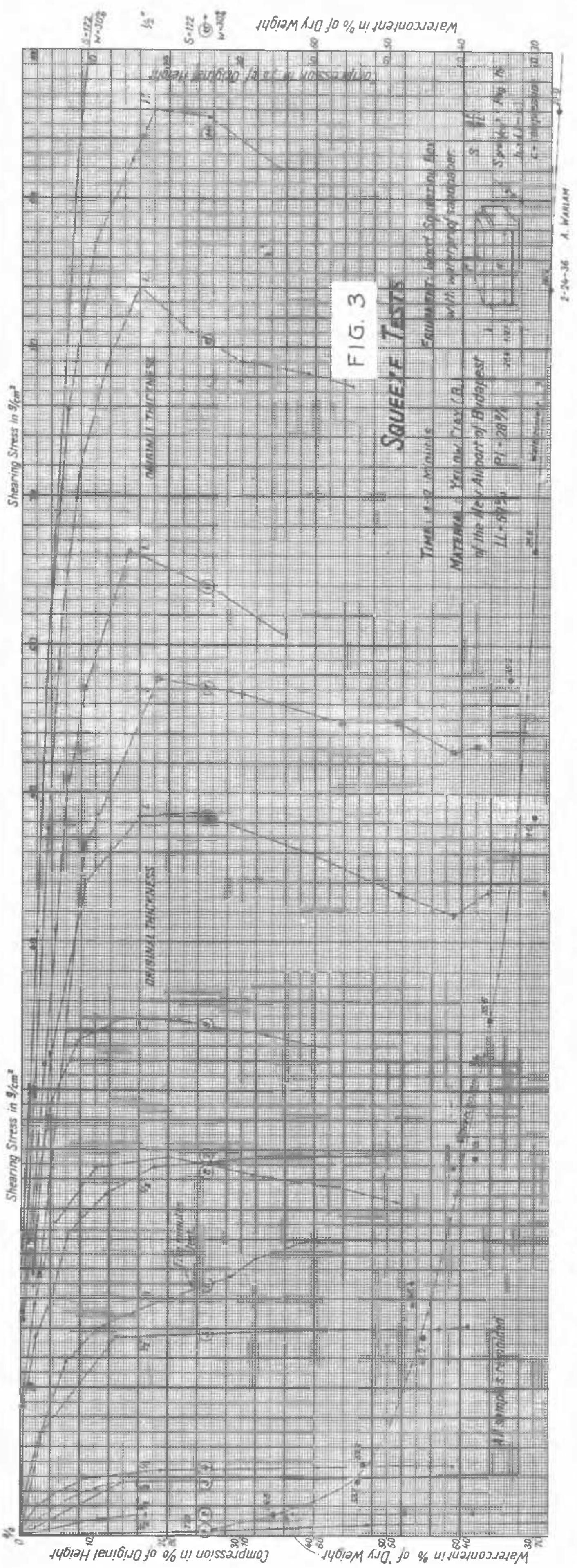


FIG. 3
Squeeze Tests
Equipment: Lead Squeezing Box with water proof sandpaper
Time: 1-10 minute
Material: Yellow Clay (B) of the New Airport of Budapest
LL = 50% PI = 28%
Original thickness
All samples remolded
Shearing Stress in g/cm²
Watercontent in % of Dry Weight
Compression in % of Original Height
2-24-36 A. Waram

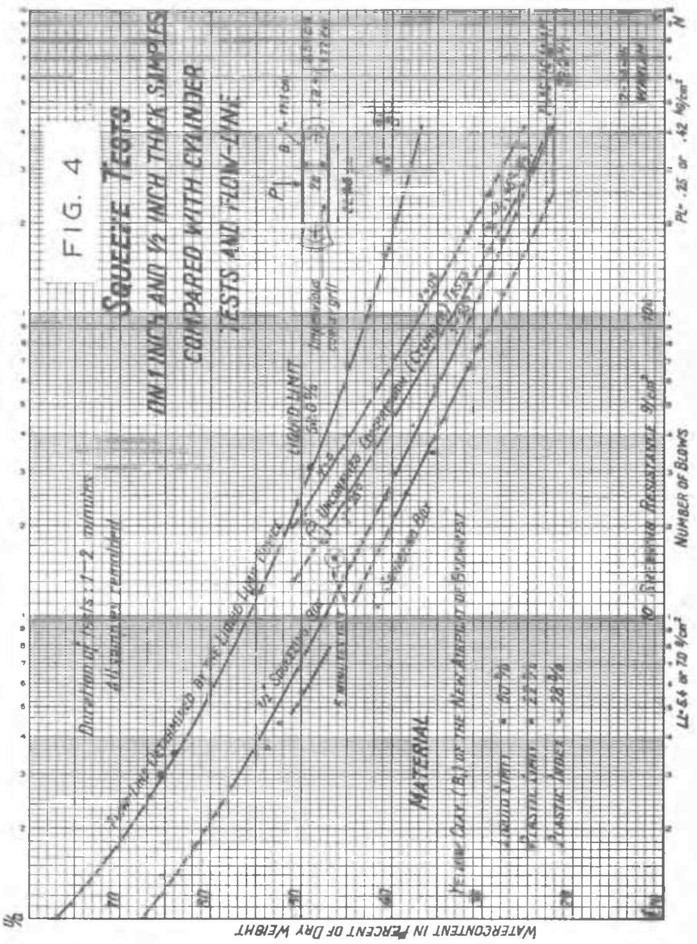


FIG. 4
Squeeze Tests on 1 inch and ½ inch thick samples compared with cylinder tests and flow-line
Duration of tests: 1-2 minutes
All samples remolded
Flow-line determined at the Liquid Limit Device
½" Squeezing Box
1" Squeezing Box
Unconfined Compression (Cylinder) Tests
Liquid Limit 50.0%
Material
Yellow Clay (B) of the New Airport of Budapest
Liquid Limit = 50%
Plastic Limit = 22%
Plastic Index = 28%
Watercontent in Percent of Dry Weight
Shearing Resistance g/cm²
Number of Blows
LL = 5.4 or 7.0 g/cm²
PL = .35 or .42 kg/cm²

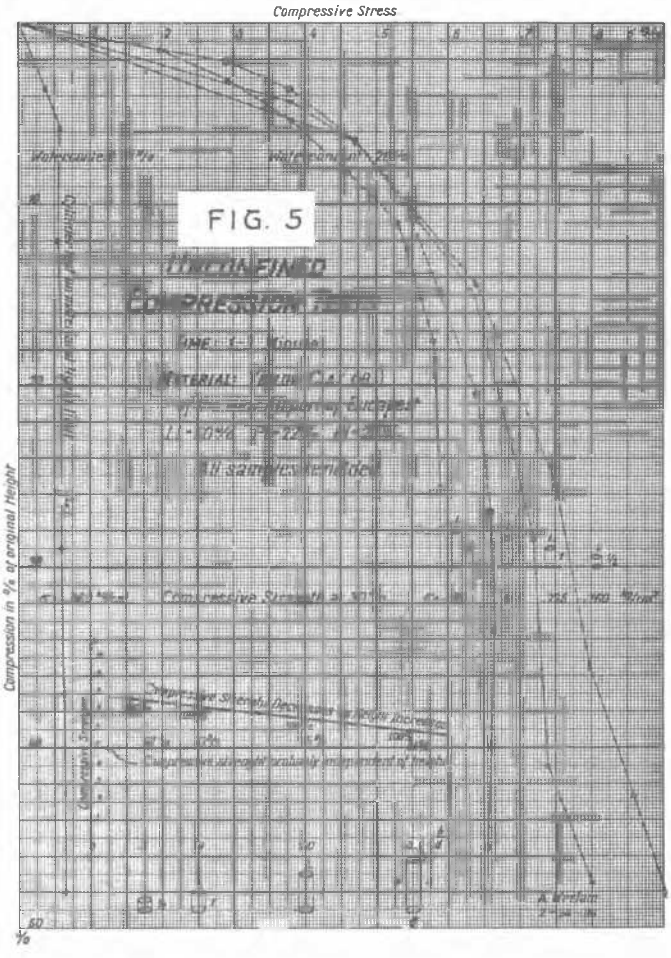


FIG. 5
Unconfined Compression Tests
Time: 1-1 minute
Material: Yellow Clay (B) of the New Airport of Budapest
LL = 50% PL = 22% PI = 28%
All samples remolded
Compressive Stress
Compression in % of original Height
Compressive Strength at 30%
Watercontent 28%
A. Waram

indebted for valuable advice. The soil tests were begun in the Soil Mechanics Laboratory of the Graduate School of Engineering, Harvard University, and continued at the Technical University of Budapest, Hungary.

No. D-13 PROGRESS REPORT ON AN INVESTIGATION OF THE SHEARING RESISTANCE OF COHESIONLESS SOILS

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Note: Letters in parenthesis indicate references listed at end of paper.

The general relation between the shearing resistance of a cohesionless soil and the normal pressure has been known for many years. It may be expressed by Coulomb's law $s = n \tan \varphi$ in which s represents the shearing resistance, n the normal pressure and φ the angle of internal friction of the material. Many tests have shown that this straight line relationship is correct for large normal loads. It has, however, been an open question as to whether this same relationship is correct for very light normal loads. In order to investigate this question a shearing apparatus was developed which yielded accurate results over a range of horizontal load from 0 to 8.5 kg. The essential features of this apparatus are shown in Fig. 1. Horizontal load is applied by allowing water to flow from an accurately calibrated tank into a counter-balanced loading tank. The shearing load and the counter-balanced force are transmitted by flexible cords over large ball bearing pulleys. The amount of horizontal load applied is measured by a manometer on the loading tank. This force is measured to the nearest 5 grams. The minimum obtainable values of the normal pressure depend upon the weights of the piston and upper frame of the shearing box, the area of the box and the weight of the sample above the shear plane. Thus for the shearing box with an area of 36 cm the minimum normal pressure obtainable was approximately 15 grams per sq cm.

Fig. 2 shows the general type of shearing boxes used in this investigation. It is the type originally designed by Terzaghi and Casagrande (1), (2). Boxes of this type of three different areas, and employing several types of gratings, were used.

In general two distinct types of cohesionless soils were used for extensive investigation under small normal loads. They are Ottawa sand of various grain sizes and sharp angular crushed quartz, also in various grain sizes.

In order to obtain consistent results the samples in the loose sand were placed in the shearing box by pouring from a spoon from a uniform height. They were carefully smoothed to a standard thickness with a metal templet. The samples for the test in the dense state were compacted by a standard number of blows with the tamping device shown in Fig. 4. All samples were oven dried before testing and were kept in desiccators until just before placing in the shearing boxes. Fig. 3 shows the results of approximately 300 tests on Ottawa sand in the loose and dense states. The range in normal loads was between .015 kg/cm^2 and 2.15 kg/cm^2. Fig. 5 is perhaps a more instructive way to study the results of these tests. The ratio of the horizontal load at failure to the vertical load is plotted against the normal pressure. Results which are horizontal lines as shown in Fig. 5 are conclusive evidence that the straight line relationship between normal load and shearing resistance does hold also for very small values of the normal pressure. Each value of the shearing resistance for a definite normal pressure represents approximately 8 tests. In Fig. 5 the range in values for any given normal load is shown as well as the average value for all tests at that normal load.

Fig. 6 shows the results of similar tests made on angular grained crushed quartz over the same range in normal loads. These tests were conducted on three different sizes of the crushed quartz, using for each material two different types of gratings. This figure shows that the average value of the ratio of the horizontal load to the normal load is constant for each material. The deviation in the angle of internal friction due to the type of grating used for these three materials varies between one-half and three quarters of a degree.

At the outset of this investigation it was decided to use shearing areas larger than the 36 sq cm area used by Dr. Casagrande and Mr. Albert (1) in order to obtain more accurate results. The first shearing box constructed had an area of 240 sq cm. The results of tests with this box did not check with the results of the earlier tests. Investigations showed that the same material tested side by side in the large box and small box yielded noticeably smaller values of the shearing resistance for the large box. Thus one of our first problems was to locate the source of this discrepancy and a means of correction for it. We have constructed boxes with shearing areas of 240 sq cm, 120 sq cm and 36 sq cm. Fig. 7 and 8 show the results of tests with these three boxes of different areas on two different materials. We do not feel that at the present time we have sufficient information to completely explain the variation in these results or to establish a correctional factor. In order to do this it will be necessary to construct boxes with considerably larger shearing areas, in addition, it will be necessary to study the effect of the shearing area on tests of different materials.

At the present time an extensive study of the effect of grain size and grain shape on the shearing resistance is in progress. In addition, the change in volume of these materials in the loose and dense state during shear is being studied. Fig. 10 and Table A show the results of the tests on the first material to be studied, a crushed quartz in the loose state. This quartz was carefully separated by screening into 10 samples which varied in average grain diameter from .26 mm to smaller than .07 mm.