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No. A-4

REPORT ON AN APPARATUS FOR CONSUMMATE INVESTIGATION OF THE MECHANICAL PROPERTIES OF SOILS

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Introduction. The mechanical properties of a soil are defined as the relations between the values of the principal stresses and the values of the principal strains at any point, provided that the directions of the principal stresses remain constant and, in case of anisotropy, coincide with the axes of anisotropy. Consequently, in order to investigate completely the mechanical properties it is necessary and sufficient to expose the soil specimen to a homogeneous (A stress system is homogeneous, if the stress ellipsoid is the same at all points) stress system, the values of the principal stresses being individually varied in an arbitrary way, and to measure the resulting principal strains. A testing apparatus designed to meet these requirements is described below; first, however, the reasons that led to its construction are given.

The mechanical properties of the soils decide the bearing capacity and the settlements of foundation plates and piles, the stability and the elastic movement of retaining walls, sheet pilings and anchor plates, etc. They are indispensable for all calculation of foundation structures and must serve as a basis for any rational classification of the soils for foundation purposes.

Of all soil testing devices such apparatuses, only, in which the stress system applied on the specimen is homogeneous, give unbiased information on the mechanical properties. The results obtained from them are not influenced by irrelevant circumstances and can therefore be directly used for calculation or classification. Such apparatuses are, for instance, the Oedometer, the shearing apparatus and the compressive strength apparatus.

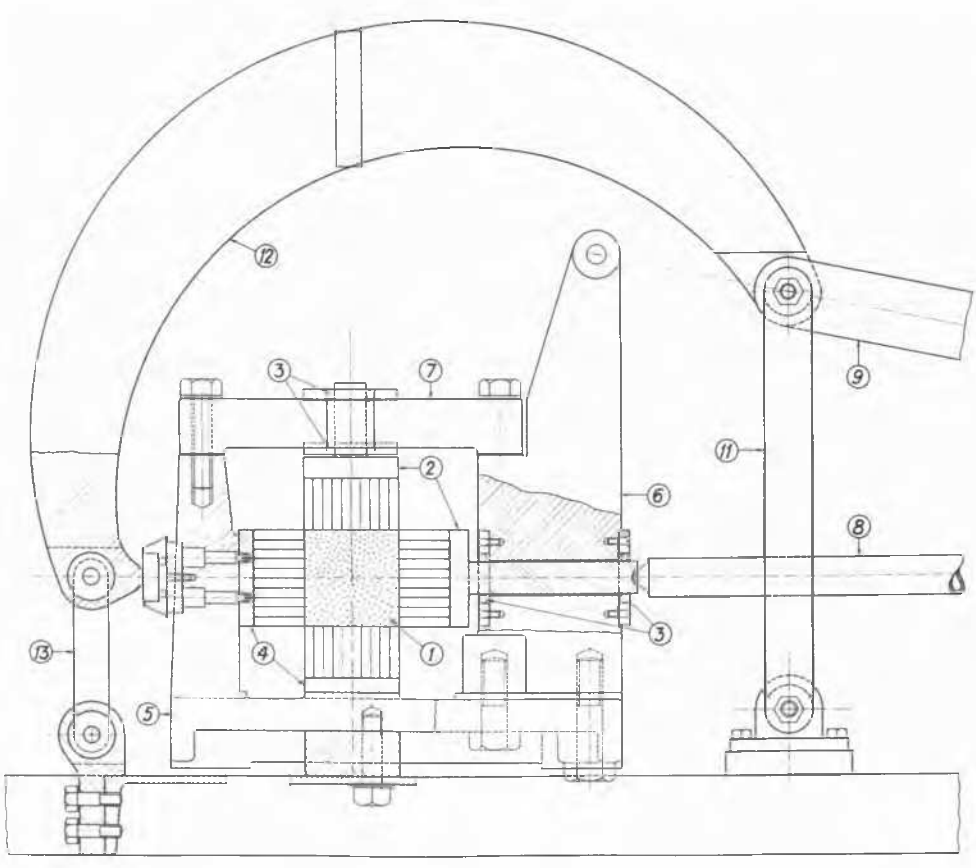

Fig. 1
Vertical section through apparatus

Every result obtained from tests at which the stress system is heterogeneous represents a conglomerate of the mechanical properties of the soil and such irrelevant circumstances as the size and shape of the specimen, the properties of the apparatus, etc. Such tests are, for instance, the flow limit test, the cone test, the dynamic test, model tests, and test loadings on the ground surface and in drill-holes. Even if these tests are standardized in detail, their results can be used indirectly only and only on condition that the measured quantity is bound to the mechanical properties by a definite relation. For some of them such relation may exist, but for none this has been proved.

The apparatuses used so far, in which the applied stress system is homogeneous, are designed for a few special stress cases only, which, moreover, can be but partially investigated, certain stress components remaining unknown. Therefore, our knowledge of the mechanical properties is still fragmentary. In the author's opinion it is most desirable that our knowledge on this subject be widened, and for this purpose the new apparatus was built.

Description of the apparatus. The soil specimen is a 62 x 62 x 62 mm cube and the principal stresses are applied perpendicularly to its surfaces. Fig. 1 shows a vertical principal section through the cube and the apparatus; this section and the other vertical principal section are identical.

The specimen (1) is in each principal direction compressed between a steel plunger (2), steered in two ball bearings (3), and a steel reaction plate (4). The six bearings and the three plates are screwed on to a cast iron frame, consisting of elements (5, 6, 7) connected by screws. The frame is mounted on a stand of steel channels and tubes.

From each plunger and reaction plate the pressure is transferred to the specimen by 100 brass rods, 6 x 6 x 32 mm, resting with their spherical ends against the plunger, or plate, and with their other ends, which are plane, against the specimen. The play between the rods, which is 0.2 mm at the beginning of the test, is later on increased or decreased, according to the deformation of the cube. The rods have been inserted in order to eliminate the friction, which otherwise would arise between the plunger and the specimen and which no lubrication could suppress.

When a specimen is brought into the apparatus the 600 rods are kept in position by a system of brass frames and steel-sheets, which are removed later on when a small pressure has been applied on the three plungers. If the material to be tested is such as might be squeezed out between the rods, the specimen is covered by a thin rubber skin. If the specimen holds water, this rubber skin is on the top side substituted by a pervious skin, and on the vertical sides extended upwards so as to form a basin communicating with the water in the voids of the specimen. When testing coarse sand, no skin must be used, lest the grains be squeezed into it and thus unobserved deformation of the specimen take place.

The force on each of the two horizontal plungers is exerted by a horizontal pressure bar (8) and a tension bar (9), the latter lying above the former in a slope of 1 to 5. As shown in Fig. 2, the two bars are connected at their outer ends in a joint, in which a loading water tank (10) is suspended. Hereby the vertical load is transformed into a 5 times greater horizontal pressure on the plunger. The upper end of the tension bar was at first connected to the cast iron frame by means of a bearing. As, however, the resulting deformations of the frame proved to influence the specimen, the frame had to be relieved from bending stresses. Therefore the reaction from the tension bar is now transmitted by a link system (11, 12, 13) to the other side of the frame exactly behind the centre of the reaction plate.

The load on the vertical plunger is applied by means of a horizontal beam above the cast iron frame, forming an angle of 45° with the plane of Fig. 1. Through a ball bearing one end of the beam is connected to a vertical rack fixed on the stand; at the other end a loading tank is suspended. The beam serves as an one-armed lever, the load applied on the plunger representing 5 times the weight of the tank.

The loading tanks are supplied with gauge glasses, permitting direct reading of the pressure exerted on the specimen. The maximum pressure is 13 kg per cm^2. The weights of the loading devices are counter-balanced. Each loading device is steered so as to move in its vertical plane only; it can also be fixed in any position in this plane. During the test the pressure bars and the beam can be readjusted into horizontal position without disturbing the specimen. In this way the small variations of the lever ratios ($< 1\%$), which the movements of the plungers otherwise would cause, can be prevented.

Whenever the three principal stresses are to be altered, it must be done in such a way that, at any moment during the alteration, the proportion between the changes already executed is the same as the proportion between the desired total changes. This is performed automatically by a special arrangement, partly visible

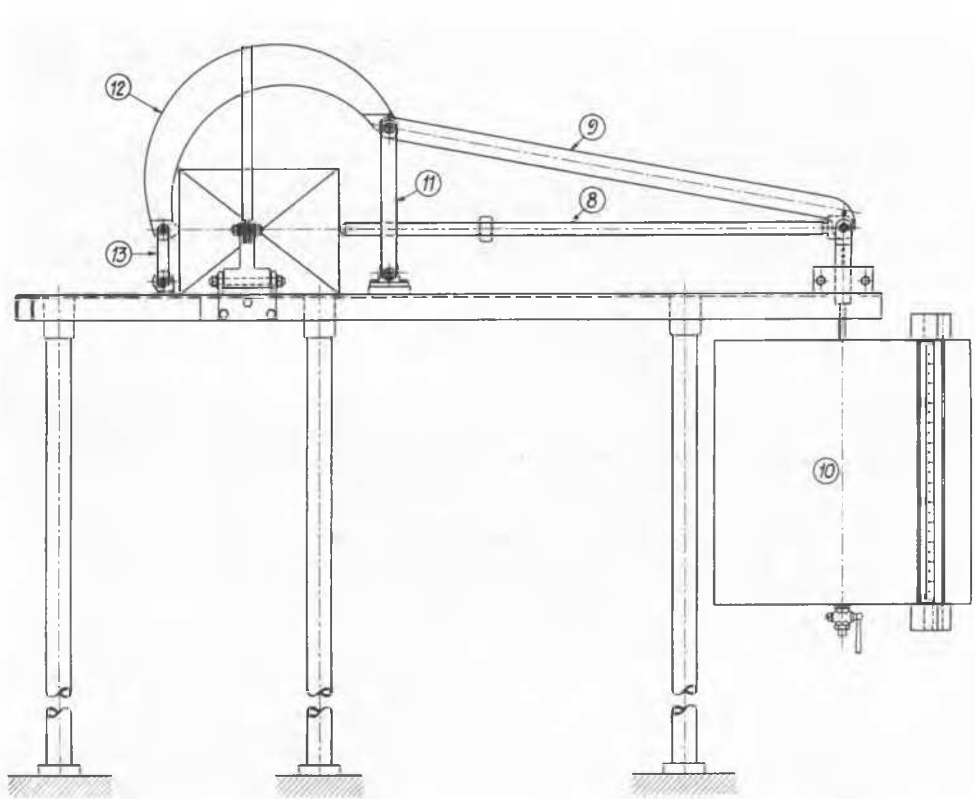

Fig. 2
Arrangement for application of horizontal load

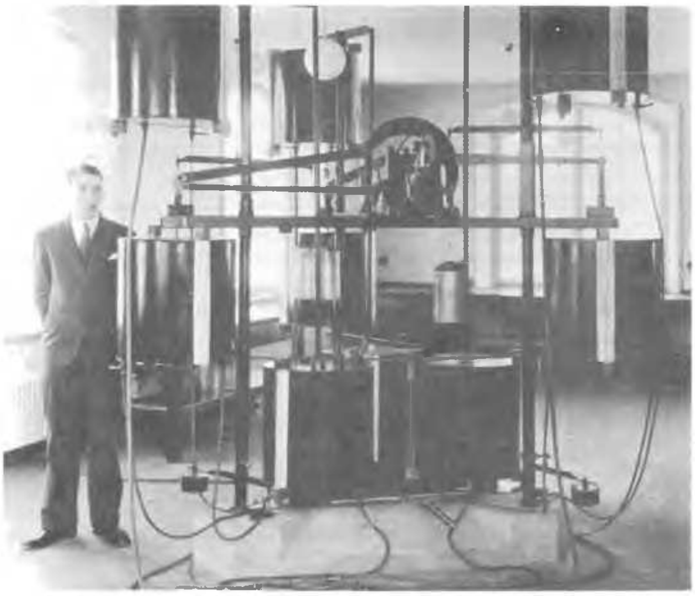

Fig. 3
General arrangement of apparatus

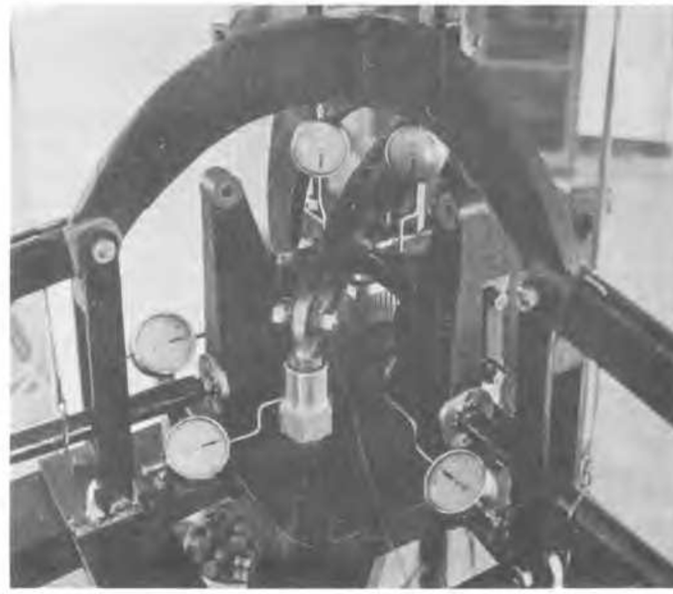

Fig. 4
Arrangement of dial gauges

in Fig. 3 and consisting of a balance plate and six auxiliary tanks communicating with the main tanks by means of rubber hoses. If the water serving as load is running in the desired proportion to or from the three main tanks, the system remains in equilibrium; if not, one angle of the balance plate will sink and thereby throttle the hose that discharges too much water.

The movement of each of the three plungers is measured by two dial gauges mounted on the cast iron frame and permitting readings with an accuracy of 0.001 mm. The weight of the feelers of the four horizontal gauges is counterbalanced. As may be seen in Fig. 4, the six gauges are placed at the same distance from a certain point, from which they can be read without parallax. When testing materials liable to a considerable time effect the readings can be automatically registered by a film camera turned by a clockwork. While the test is going on, the apparatus can be left without attendance for three days at a time.

By a series of minute tests it has been ascertained, that the deformations of the cast iron frame are insignificant and that the arrangement for proportioning the loading water works very accurately. In order to check the friction losses of the three plungers and lever devices a water cube in a rubber skin was inserted. Even at the maximum load of 500 kg in each direction the friction was so small that a slight touch with the finger on any tank immediately put the dial gauges in motion.

Some test results. During the last three years more than 50 specimens of soils and several other materials have been tested. The results will later on be published in full. In order to prove the possibilities offered by the apparatus, however, a few of them are mentioned below. They all refer to dry German standard sand, i.e. a pure quartz sand with a grain size of 1 mm. The rate of voids was 0.67.

Three-axial compression. When exposing the sand to a three-axial uniform pressure the cubical compression varied with the pressure as shown in Fig. 5. It is remarkable, that no less than four-fifths of the compression during the first loading cycle are reversible. The test was repeated four times with new sand and the curves of the cubical compression were practically identical. On the other hand the curves of the three principal strains of each test differ considerably. This anisotropy of the sand is due to the inevitable irregularity at the packing, which also partly explains how results obtained in the Oedometer from different tests on the same sand can differ up to 40 per cent.

One-axial compression. Simultaneous compression tests on sand without lateral expansion were carried out in the Oedometer and in the new apparatus. The curve obtained from tests in the latter shows greater total but less permanent compression and less hysteresis. The difference is due to friction in the Oedometer.

At the same time the lateral pressure was obtained as a function of the axial pressure. In the literature on soils the ratio between them is supposed to be always 0.4. As may be gathered from Fig. 6, this is not true; for standard sand the ratio varies between ~ 0.5 and ~ 1.5.

By plotting the compression during this test against the mean value of the principal stresses, almost the same curve is obtained as in the test with three-axial compression. This interesting fact suggests that the cubical compression generally depends on the mean stress only. Other tests have proved this to be approximately true except in the proximity of rupture.

Two-axial compression. Tests with the same pressure in two directions and without expansion in the third one were performed on sand. The resulting compression curve lies between the curves obtained from

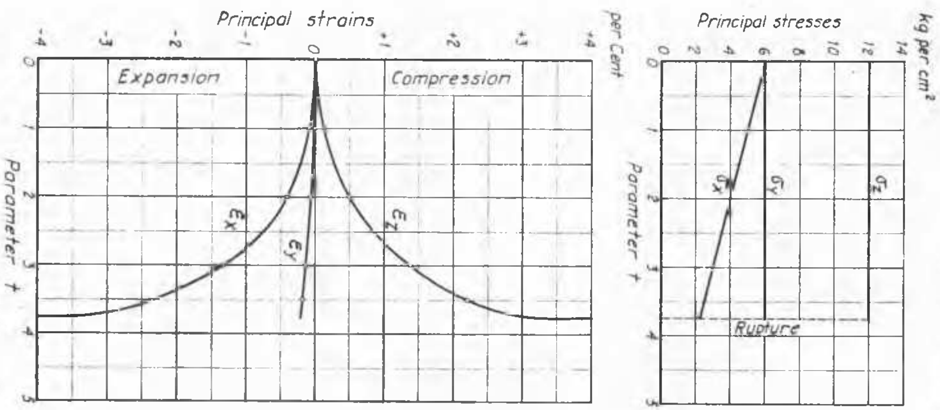

Fig. 7. Two-dimensional rupture test

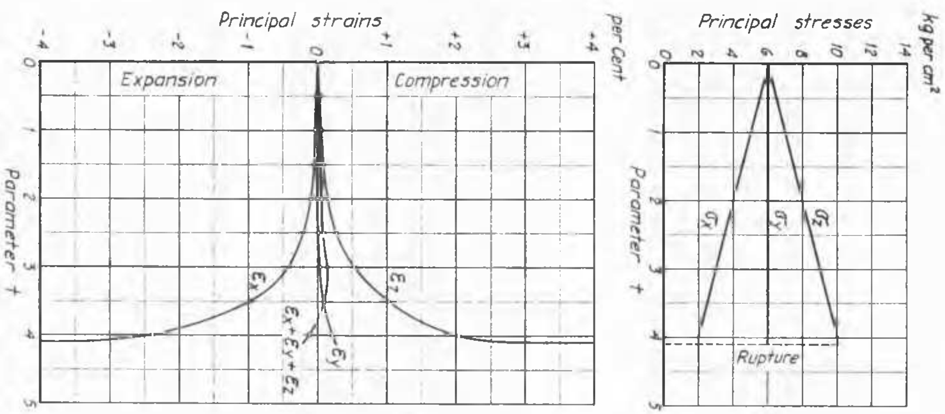

Fig. 8. Two-dimensional rupture test

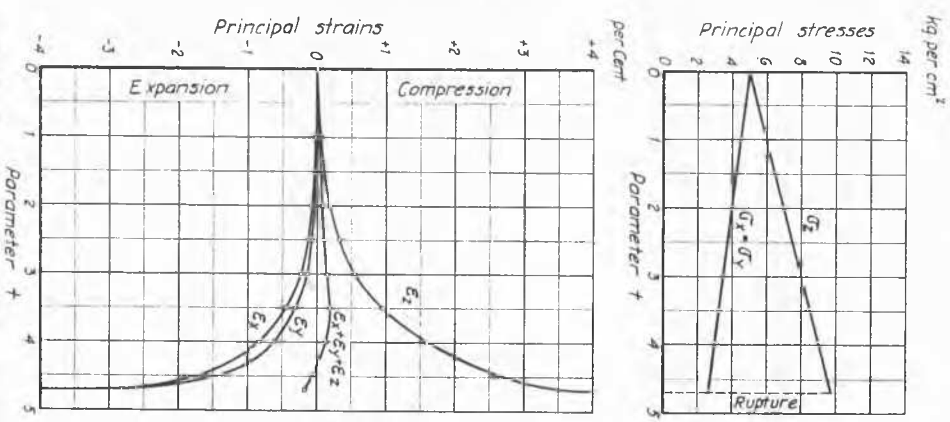

Fig. 9. Three-dimensional rupture test

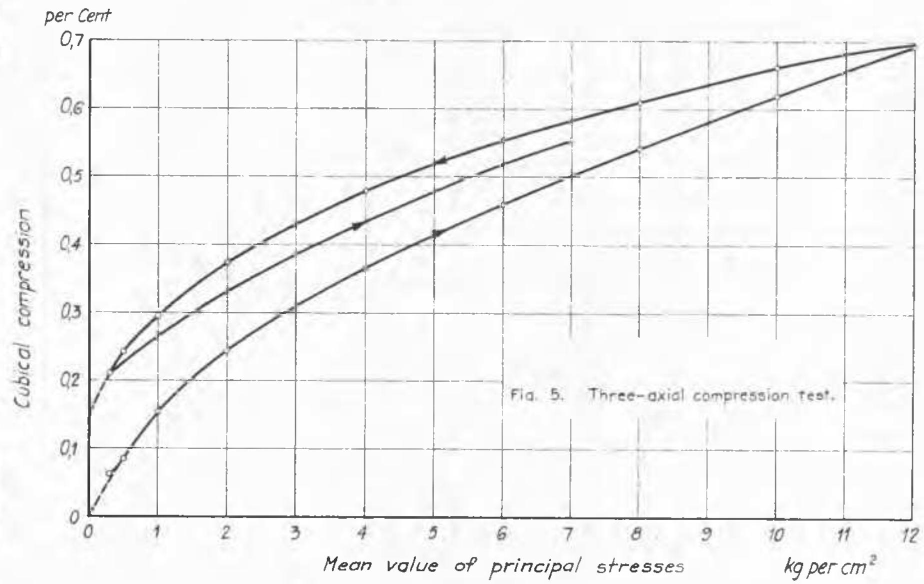

Fig. 5. Three-axial compression test.

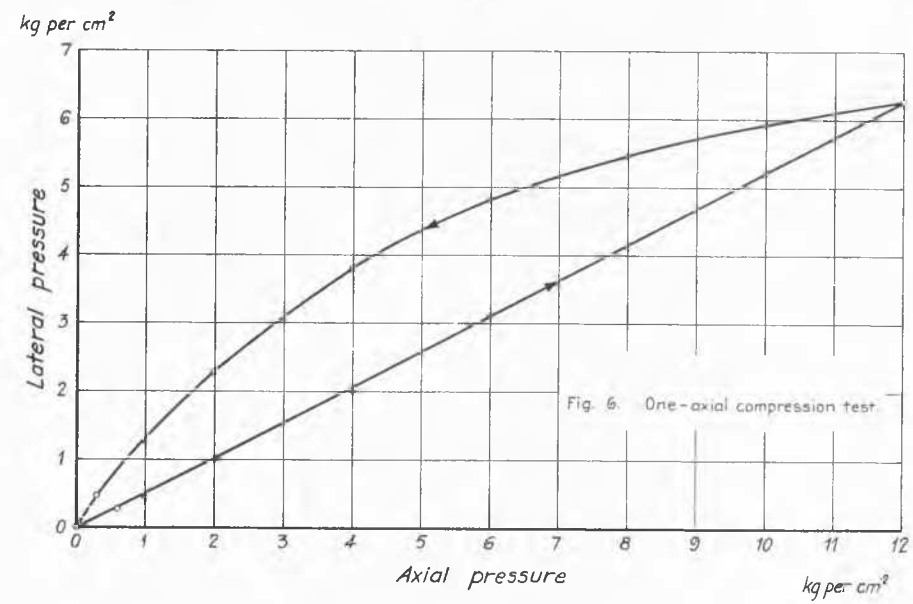

Fig. 6. One-axial compression test.

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the three-axial and the one-axial compression tests. The lateral pressure curve is similar to the curve obtained from the one-axial test but shows less hysteresis, the coefficient of lateral pressure varying between ~ 0.6 and ~ 1.0.

Two-dimensional rupture. A sand specimen was compressed in one direction until the principal stresses amounted to $\sigma_z = 12.00$, $\sigma_x = \sigma_y = 6.00$ kg per cm². σ_z and σ_y were then kept constant, while σ_x was reduced, until rupture occurred at $\sigma_x = 2.27$ kg per cm², corresponding to a coefficient of active pressure of 0.19, i.e. to an angle of friction of 43°.

The second part of the test is represented by Fig. 7, where the principal stresses and principal strains are plotted against a parameter t, defined by the condition that $\sigma_x = 6.00 - t$ kg per cm² for any corresponding values of σ_x and t.

By the results from tests of this kind it will be possible to calculate, approximately, how far a retaining wall or a sheet piling must move in the horizontal direction before the earth pressure is reduced so much that the structure can sustain it.

Another specimen was compressed in the three principal directions until the principal stresses amounted to $\sigma_x = \sigma_y = \sigma_z = 6.00$ kg per cm². Then σ_y was kept constant, while σ_x was reduced and σ_z increased, the mean stress $\frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$ being kept constant. Rupture occurred at $\sigma_x = 1.87$ and $\sigma_z = 10.13$ kg per cm², corresponding to an angle of friction of 43°, as before.

In the same way as in the previous test, this test is graphically represented by Fig. 8. The cubical dilatation $\sigma_x + \sigma_y + \sigma_z$ is also plotted on this figure. At first there is a slowly increasing cubical compression, then cubical expansion begins and rapidly increases until rupture. This expansion is always a sure indication of impending rupture.

For the sake of comparison standard sand was also tested in the Krey shearing apparatus. With a normal pressure of 3.20 kg per cm², corresponding to the pressure in the critical plane in the previous test, rupture occurred at a shearing stress of 2.10 kg per cm², thus giving an angle of friction of 34°. The divergence of this value from the value obtained in the new apparatus depends on stress irregularities in the Krey apparatus. The fact that the movement before rupture was 10 times larger in the Krey apparatus than in the new one, also suggests that the Krey shearing test is influenced by irrelevant secondary phenomena.

Finally it may be mentioned that the angle of repose of the standard sand is $\sim 40°$.

Three-dimensional rupture. A sand specimen was compressed in the three principal directions until the principal stresses amounted to $\sigma_x = \sigma_y = \sigma_z = 5.00$ kg per cm². Then σ_x and σ_y were decreased and σ_z increased in such a way, that constantly $\sigma_x = \sigma_y$ and $\sigma_x + \sigma_z + \sigma_y = 15.00$ kg per cm². Rupture occurred at $\sigma_x = \sigma_y = 2.65$ and $\sigma_z = 9.70$ kg per cm², corresponding to an angle of friction of 35°. The divergence of this value from the value obtained from the two-dimensional tests denotes the influence of the third principal stress. The test is graphically represented by Fig. 9.

Acknowledgements. The apparatus described above was built in connection with investigations carried out by Vattenbyggnadsbyran (VBB) of Stockholm, acting as Consulting Engineers for the Svir 3 and the Svir 2 hydro-electric power plants in Soviet-Russia. The author is greatly indebted to the Chief Engineer of the Svir plants, Professor Henry Graftio, and to several senior engineers of the VBB. By the favour of Professor Carl Forssell, of the Technical University of Stockholm, the investigations could be performed in the well-equipped Laboratory of Structural Engineering of this University.

No. A-5

THE SOIL MECHANICS LABORATORY AT YALE UNIVERSITY

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The Soil Mechanics Laboratory at Yale University belongs to the Department of Civil Engineering of the Yale School of Engineering. It was established in 1930 and is located in one of the spacious halls of Hammond Metallurgical Laboratory. The writer is in charge and is the only worker. In addition to research and instruction this laboratory also does consulting work for the Connecticut State Highway Department. A graduate course in soil mechanics and another graduate course in earth and foundation engineering are offered at Yale; and student exercises along these lines are conducted in this laboratory.

Equipment. The total floor area occupied by the laboratory, deducting office space, is about 530 sq ft. There is no humid room and no constant temperature room. Instead there is free access to the general equipment of the Hammond Laboratory (analytical balance room; mechanical work shop; large gas oven for drying large samples; hot plates and gas burners; photographic room; installation for routine chemical analysis; microscopes, etc.). There is the following apparatus for the classification of soils: (a) a mechanical Tyler sieve shaker, belonging to Hammond Laboratory; a set of U.S. standard sieves; and all necessary equipment for the hydrometer test, including some new stream line hydrometers; (b) an automatic oven and sets of weighing bottles and watch glasses for water content determination; (c) picnometers, and also Le Chatelier bottle for specific gravity determination; (d) a device for determining the apparent specific gravity of a soil sample by displacing mercury; (2) equipment for determining Atterberg limits, including Casagrande's liquid limit device; (f) a standard centrifuge and all neces-