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

D. P. Krynine, Research Associate in Soil Mechanics, Yale University

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-

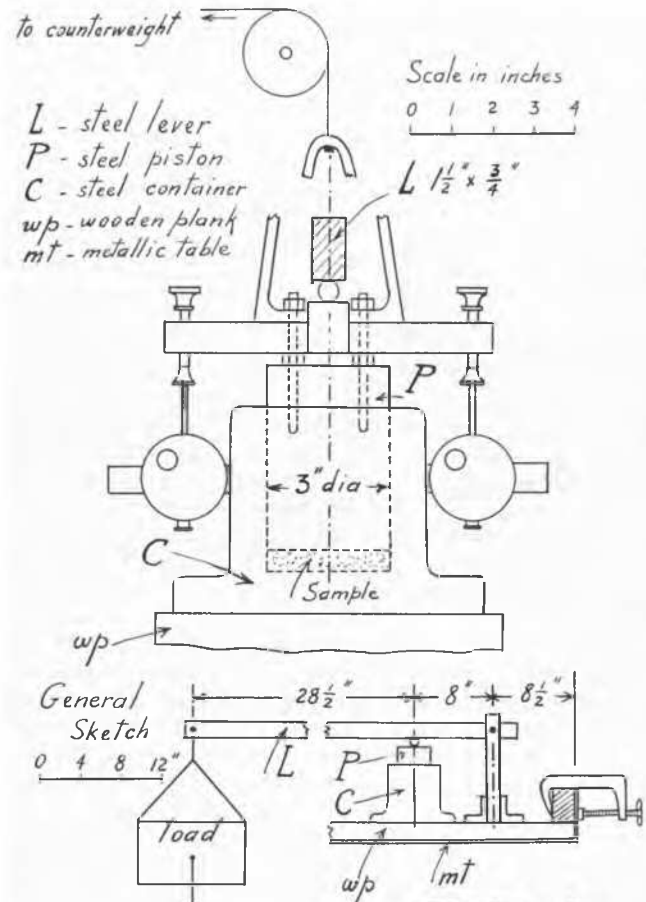


FIG. 1

Compression Apparatus for Confined Sand Samples.

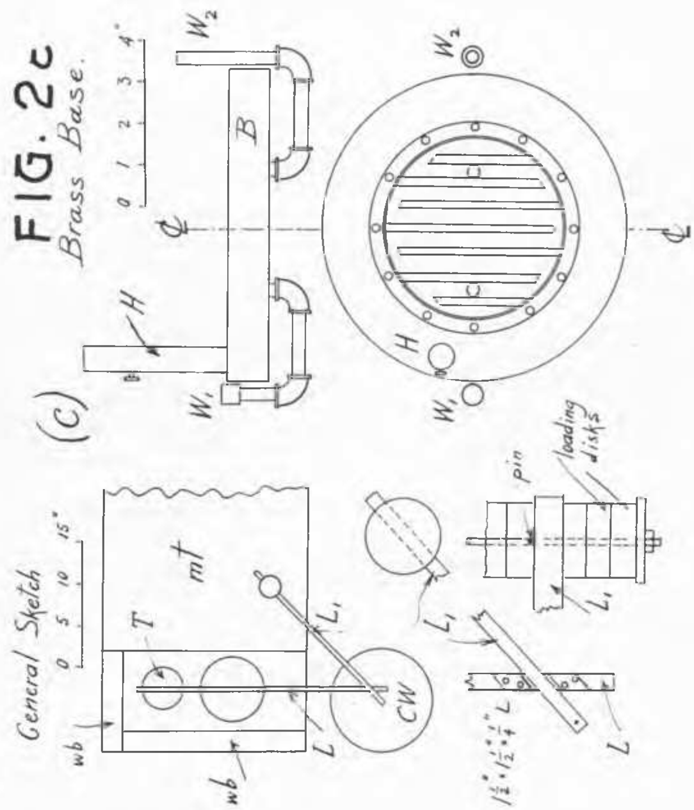


FIG. 2abc. Consolidation Apparatus.

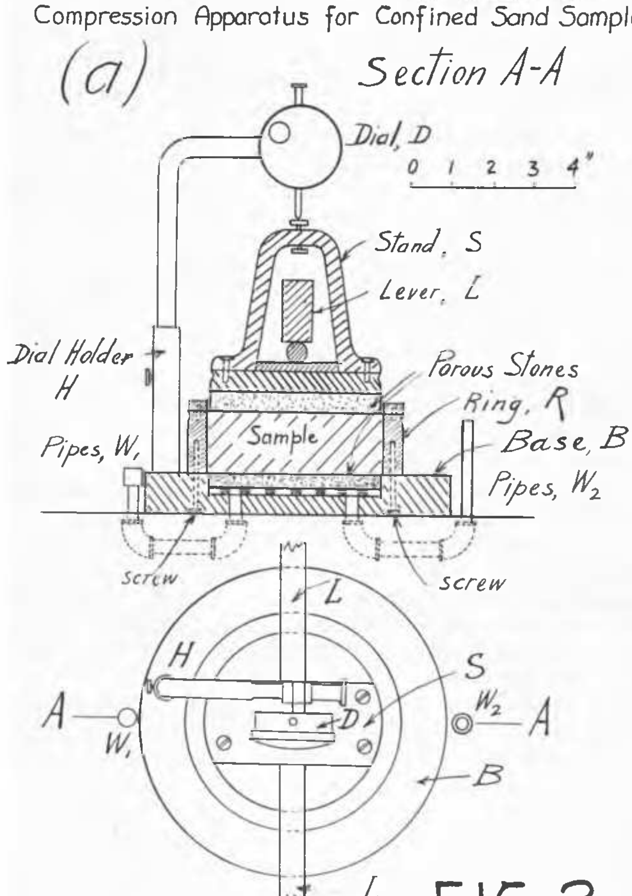
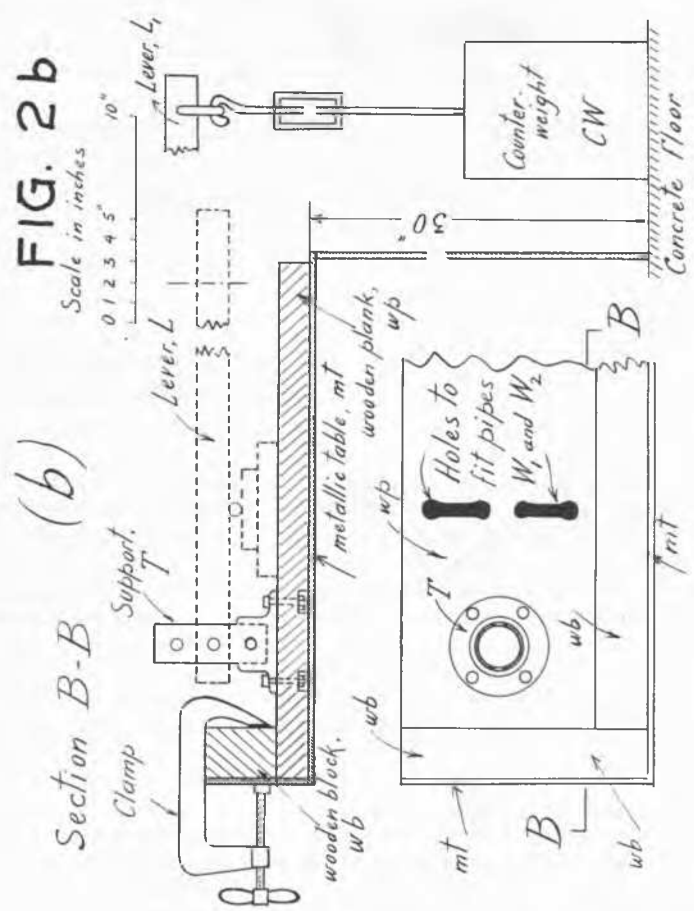


FIG. 2a



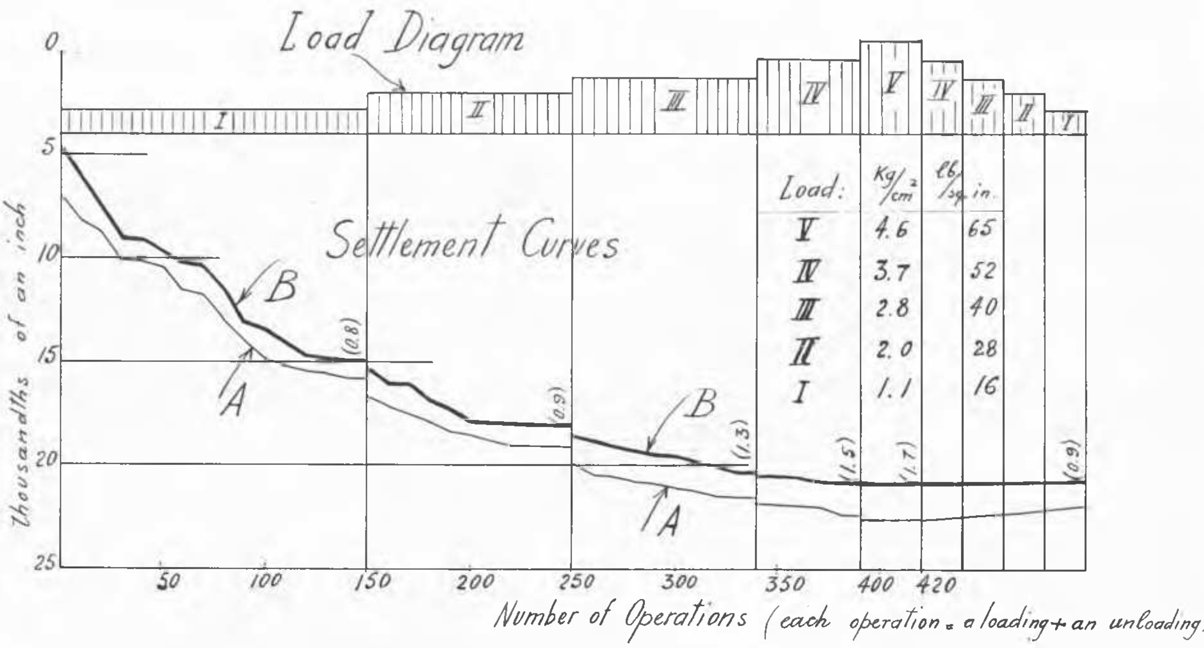


FIG.5. Settlement Curves of a Confined Sand Mass.

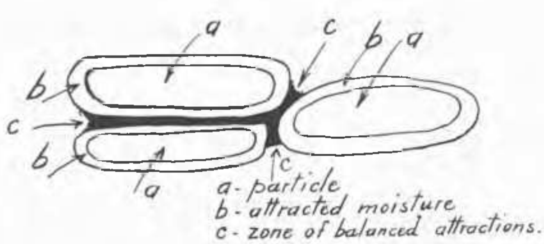


FIG.3. A preliminary sketch explaining the consolidation process.

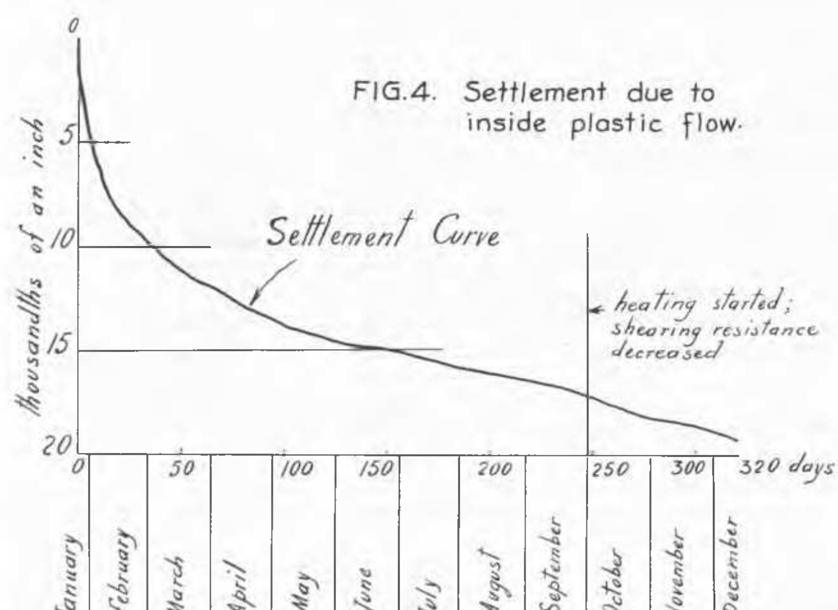


FIG.4. Settlement due to inside plastic flow.

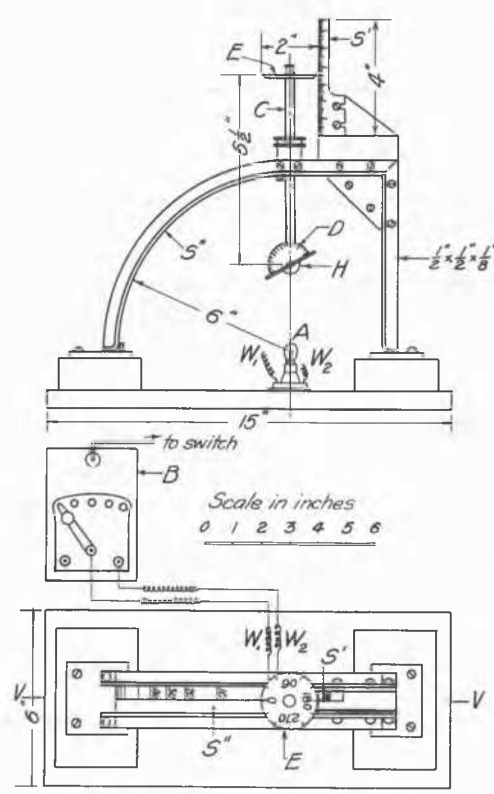


FIG.6. Stereogoniometer.

sary equipment for determining both the centrifuge (Proc., Eleventh Annual Meeting of Highway Research Board, part I, pages 199-216 (1932)) and the field moisture equivalent. The construction of a shearing machine is included in the plans for the academic year 1936-1937. Consolidation and compression apparatus are located on a heavy metallic table; and since the floor is of concrete, there are practically no vibrations. There are three apparatus on this table: (a) an original Terzaghi odometer; (b) an apparatus for studying elasticity and compressibility of sands shown in Fig. 1; (c) a clay consolidation apparatus (Fig. 2: A,B,C). Dry Sands also may be studied by the latter apparatus in which case the porous stones shown on the plans, are replaced by steel disks of equal size. The apparatus mentioned are placed on wooden planks 1 1/2 in thick and fixed to the metallic table by clamps. (Trans., Am. Soc. C.E., Vol. 59, p. 268, 1933). A permeability device of Casagrande's type, to accompany the consolidation apparatus, Fig. 2, is under construction. At present there is a Terzaghi permeameter and a simple device for determining the permeability of sands and other coarse materials. (Trans., Am. Loo. C.E., Vol. 59, p. 266, 1933) Capillary movement is studied not in tubes, but along a horizontal plane. For this purpose a special high table provided with barometer and thermometer; has been constructed, and observations are made from below, through a thick glass plate. ("Soil Investigations in 1928-1929", by D. P. Krynine et alii, p. 34, in Russian) There are also some apparatus for pressing metallic and wooden blocks into soil masses; a table for studying the influence of bitumina on soils; and a Proctor's needle for studying soil mixtures for fills.

Soils in the working region. The working region of the laboratory is the State of Connecticut. The whole zone is glacial and may be subdivided into: (a) Western Highland of schists and gneiss rocks; (b) Eastern Highland of gneiss and schist rocks; and (c) Central Lowland of triassic sandstone and shale rocks, with trap intrusions. There are valleys of limestone along the western boundary of the State. The principal surface soils in the Lowland are clay loams (Wethersfield; Suffield); sandy loams and various sands. At some depth there are clays in the Connecticut River valley and also in the Highlands. A Hartford clay has been studied in some detail by Terzaghi; (Ingenieurgeologie, by Redlich; Terzaghi; and Kampe, p. 345, 1929) the results of the writer's studies of Middletown clays will be checked during the construction of the new bridge over the Connecticut River in 1936-1937. The Western Highland is mostly influenced by the Charlton loam; and the Eastern Highland by sandy and gravelly loams (Gloucester; Hinckley). During the summers of 1930 and 1931 a soil survey was made by the writer in New Haven and Hartford Counties (Soil Investigations for Highway Purposes in the county of New Haven, Conn.--A manuscript filed in the Eng. Library, New York.) and an attempt was made to classify the surface soils according to their moisture equivalent and colloidal content.

Most Important Practical Investigations. In 1932 soil investigations for a bridge over the Connecticut River in East Hartford were made; and some interesting conclusions on the stress distribution were drawn from a loading test. (Engineering News Record, Vol. 109, pp. 782-784, December 29, 1932.) In 1933 a study of swelling of earth in embankments in the Western Connecticut Highland was made; results unpublished. In the same year loading tests for a bridge spanning the New Haven Railroad in Stratford were made. (Annual Report of the Conn. Society of Civil Engineers for 1934, pp. 70-81.) In 1934 and 1935 the laboratory assisted the Connecticut State Highway Department in the study of a bridge settlement in Bridgeport, Conn. In the summer of 1935 assistance was given in the soil investigations for the new bridge over the Connecticut River, between Middletown and Portland, already referred to.

Fundamental Research in Progress. In the past four years the writer has had various opportunities to observe the behavior of saturated fine sand masses and has come to the conclusion advanced in older views but subsequently denied, that the sand particles actually are coated with adsorbed moisture films. Beyond question, the behavior of a soil mass is controlled by the law of least resistance; and if an outlet is open (for instance, in an excavation) the mass under pressure rushes into this outlet as a liquid (quicksand action). The presence of moisture films is immaterial so far as the trend of this movement is concerned. The situation changes if the saturated fine sand mass is confined. In this case the mass is under the action not of a pressure, but of a shearing stress. It moves plastically and tends to bend the confining envelope. Since sand grains are not plastic, attracted moisture should be in plastic state. Generalizing this statement for the case of clay, one is led to the conclusion that the clay consolidation process is two-fold: (1) there is a neutral zone, c, between the particles marked in black in Fig. 3 where Pascal's law is valid, and (2) in the rest of the space between particles, a, there is attracted plastic moisture, b, which is gradually torn off by the shearing stress and thrown into the neutral zone as the latter is gradually evacuated by the unattracted moisture. This process could be called "inside plastic flow". To prove that the consolidation process depends on the plasticity of the material, a confined layer of rifle lead shot, about 1 1/4 in thick and 3 in in diameter has been compressed with a load of about 65 lb per sq in of the loading piston. The curve of settlement observed during 320 days is very similar to that obtained in the case of clays. Fig. 4. This research will be continued and should be finished by 1938.

Another research project concerns the elasticity of sands. A sand mass becomes elastic if loaded and unloaded a number of times with a certain unit load. Should a larger unit load be applied, the mass loses its elasticity, as shown in Fig. 5. This is an explanation why old earth roads, apparently stable, are ruined if uncommonly heavy loads pass over them even a few times. The curves "A" and "B" in Fig. 5 correspond to the total settlement of the sample in loaded and unloaded condition, respectively, so that the difference between them is the elastic rebound at the given stage of the experiment. This research is expected to be finished by 1937.

The sum of principal stresses at a given point of a loaded elastic isotropic mass is proportional to the "angle of visibility" of the foundation from the given point. To measure the angle of visibility, which is a solid angle, a special apparatus called "stereogoniometer" has been constructed. Fig. 6. Its mathematical theory is expected to be published by 1937.

The laboratory greatly appreciates the financial help received from the Connecticut State Highway Department and from the Committee on Earths and Foundations, Am. Soc. C.E. The apparatus shown in Fig. 1, 2, and 6, have been constructed in the laboratories of Yale University. The kind cooperation of Professors Samuel W. Dudley and Louis W. McKeehan is greatly appreciated.

No. A-6

REPORT FROM THE SOIL MECHANICS LABORATORY AT THE UNIVERSITY OF MICHIGAN ON TESTING APPARATUS, TECHNIQUE OF TESTING, AND INVESTIGATIONS IN PROGRESS

W.S. Housel, Assistant Professor of Civil Engineering in the University of Michigan at Ann Arbor

1. State Highway Laboratory at University of Michigan, Ann Arbor, Michigan. Organized and operated jointly by the Michigan State Highway Department and University of Michigan.
   - a. Subgrade soil surveys and laboratory tests started in September, 1925, by the State Highway Department.
   - b. Research on bearing value of soils for foundations started by Civil Engineering Department in 1927.

2. Present soil work in charge of William S. Housel, Assistant Professor of Civil Engineering and Research Consultant, Michigan State Highway Department.
   - a. Subgrade soil surveys initially in charge of V. R. Burton and A. C. Benkelman. Soils for highway purposes combined with research on bearing value of soils in 1933. Regular staff--3 men; average temporary staff--6 men. The State Highway Department also maintains a trained staff of from 3 to 8 field men for soil surveys in charge of O. L. Stokstad, Soils Engineer.

3. Soil Mechanics Laboratory maintained for research, instruction and routine testing in connection with highways and structures.

4. Description of Equipment.
   - a. 1300 square feet devoted exclusively to soils work with auxiliary facilities frequently used for miscellaneous soil tests in other units of the Highway Laboratory. These auxiliary units consist of chemical, concrete, cement and aggregate laboratories, with total floor space of approximately 17,000 square feet.

     Two moist rooms, one of which is equipped with automatic control and recording of temperature and humidity.

     Cold room with automatic temperature control down to -40°.
   - b. Apparatus for classification of soils. (Note. General equipment itemized below sufficient for routine testing, student instruction, and research.)
     - (1) Particle size.
       - (a) Standard equipment for sieve analysis.
       - (b) Equipment for Bouyoucos Hydrometer analysis.
       - (c) Wagner turbidimeter.
       - (d) Sharples Centrifuge, turbine drive, 50,000 r.p.m., centrifugal force 62,000 x gravity.
       - (e) Pyconometer and elutriation methods.
     - (2) Particle shape.
       - (a) Petrographic microscopes.
     - (3) Water content--electric drying ovens with constant temperature control.
     - (4) Volumetric analysis giving per cent solids, water and air in terms of original volume.
     - (5) Chemical analysis for organic matter and calcareous material. Loss on ignition for organic matter.
     - (6) Specific gravity--displacement in mercury and water or kerosene.
     - (7) Plastic limit, lower liquid limit and plasticity index. Equipment as required by proposed A.S.T.M. Tentative Standards.
   - c. Shearing Tests.
     - (1) Penetration method. A.S.T.M. Proceedings Vol. 35, Part 2, p. 473.
     - (2) Laboratory shear tests.
       - (a) Cohesive soil. Loc. cit. p. 482.
       - (b) Granular material. Loc. cit. pp. 496 and 497.
   - d. Compressive Strength Tests.
     - (1) Two balance beam loading machines (Fig. I), 5,000 pounds capacity. Loc. cit. p. 494.
     - (2) Large compression machines available in other laboratory units.
   - e. Consolidation Tests.
     - (1) Vibration machine and other equipment to produce maximum consolidation and to provide accurate control of density and voids of various soils prepared for laboratory tests. Loc. cit. p. 495.