INSTRUMENTS AND METHODS FOR STUDYING THE RHEOLOGICAL PROPERTIES OF CLAY SOILS

N. V. Zhukov and A. M. Gutkin

Inzhenerno-Fizicheskii Zhurnal, Vol. 10, No. 3, pp. 396–404, 1966

UDC 532.135

There is an ever-growing need for the further development of the rheology of soils. However, specially designed instruments are required for studies in this area. The instruments used for the rheological investigation of disperse systems are not suitable for solving many of the practical problems associated with the design of foundations. The instruments used in soil mechanics are so constructed that they cannot satisfy certain of the requirements of rheological tests. This article reviews existing instruments for the study of soils and analyzes their usefulness for rheological research. The state of stress of the sample in different instruments is investigated and the processes that take place in the sample during testing in open and closed systems are examined.

I. ANALYSIS OF INSTRUMENTS FOR THE RHEOLOGICAL STUDY OF CLAY SOILS.

1. **Standard shear box.** This instrument has been used by S. S. Vyalov [3], I. M. Gor'kova [4], S. R. Meschan [6], and others for studying the rheological properties of soils. The advantages of this instrument include simplicity of construction, the comparative ease with which the samples can be prepared for testing, the simple testing method, and the short drainage path.

Its principal disadvantage is the nonuniformity of the stress and strain states of the sample during testing (Fig. 1). Consequently, the stress distribution inside the sample is not known. The shape and height of the shear zone depend on the strain rate and the properties of the soil and may vary during testing. If the test lasts several hours, then, as shown by V. S. Fadeeva [18], during the test a homogeneous sample of clay soil with coagulation bonds between the particles becomes inhomogeneous: parallel orientation of the particles is observed in the shear zone, accompanied by the migration into this zone of the finest fractions of the disperse phase and moisture. The deformation is almost entirely restricted to a small part of the height of the sample. Accordingly, the determination of the relative shear strains, the rate of shear flow and the rheological parameters—viscosity, shear modulus, etc.—involves considerable errors. A disadvantage of the shear box is the reduction in the working area of the sample during testing—the so-called progressive failure effect. This gives a distorted idea of the strength of the sample even in short-time tests [19]. In long-time tests the importance of this factor is particularly great, since a reduction in the working area of the sample intensifies the process of concentration of structural inhomogeneities, microparticles, and moisture in the shear zone. In long-time experiments the moisture of the sample diminishes owing to desiccation. The volume strains are not checked during the test, which complicates the interpretation of the results.

2. **Triaxial compression test apparatus (stabilometers).** These instruments (Fig. 2) have been used for rheological studies by Haefeli [12], Gol'dshtein [9], Trollope and Chan [14], Murayama [13], and others.

The sample is again under conditions of nonuniform deformation, as may be seen from a visual examination of the sample after testing. As may be seen from Fig. 2, the deformed sample is barrel-shaped. The cross-sectional area of the sample F varies over the height. During creep under constant axial load the value of F may vary so much that the normal stresses are more than halved in a comparatively short time (about two hours) ([3], p. 75). In order to keep the normal stresses constant, it is necessary to regulate the axial load during the test—to increase it in proportion to the increase in F. However, since the law of variation of F is not known in advance, it must be verified during the test. This is quite a complicated problem, since the change in axial load must follow quite quickly after the change in area F. Since the value of F varies over the height of the sample, it is not quite clear to what area—maximum or average—the axial load should be referred in determining normal stresses. Bishop and Henkel, for example, recommend dividing the axial load by the average area.

The barreling effect is well-known in testing metals. Here, in constructing the true stress-strain relations, it is customary to use such laborious methods as, for example, the method of Taylor and Kuini [27], which consists in compressing a cylindrical specimen under successive small load increments, and after each application of load cutting from the now barrel-shaped specimen a new specimen in which the original proportions are restored. It is important to note however that "barreling" is accompanied by the destruction of the original physical homogeneity of the sample. In solid samples the formation of denser nuclei is observed [20], which complicates the stress state, while in specimens of plastic clay the different intensity of deformation leads to a considerable redistribution of pore water in the sample [17, 21]. In the review by Cassagrande and Wilson [21] there are references to papers in which it is shown that this redistribution varies according to the time of axial loading, the structure and mineralogical composition of the clay and its degree of preliminary compaction.

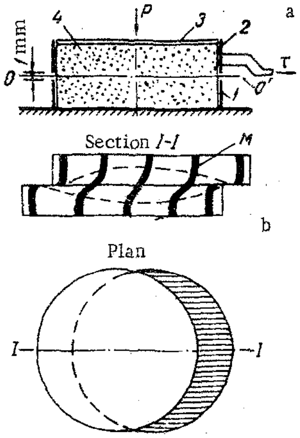

Fig. 1. Standard shear box: a) diagram of instrument (1—fixed ring, 2—moving ring, 0—0'—shear plane, 3—pressure plate, 4—sample); b) state of sheared sample (M—contrast clay tracers showing nature of deformation of sample, the broken lines denote the shear zone).

For normally compacted clay in slow tests, the moisture content increases in the end regions due to a decrease in moisture content in the middle of the sample, whereas in overcompacted clays and clay shales the opposite effect is observed. If clays are tested in the closed system* so rapidly that the redistribution of water cannot take place, then it is possible to observe a nonuniform distribution of pore pressure (the pore pressure at the center of the sample and at the end faces may differ by 4–5 times). The stabilometer does not exclude the progressive failure effect, as may be clearly seen from Fig. 2.

A. Ya. Turovskaya has shown [22] that in testing samples in the stabilometer the deformation may also be confined to a narrow shear zone, an effect accompanied by orientation of the particles and concentration of moisture. Consequently, the magnitude of the zone in which deformation occurs becomes indeterminate. Calculation of the relative strains becomes more complicated. Investigation of the nominal instantaneous strains is made difficult because the rapid motion of the ram causes a pressure wave in the liquid filling the chamber [23]. A detailed analysis of other, less important shortcomings of the apparatus (ram friction, diffusion of water through rubber tube in long-time tests, etc.) is given in [23, 21]. An advantage of the apparatus is the possibility of testing soils and conditions of combined stress in both the open and closed systems. These tests simulate the behavior of the soil in the foundations of structures in many practical problems.

3. **D. M. Tolstoi's apparatus.** This apparatus is used for studying the rheological properties of soils (Fig. 3) in the Savarinskii Laboratory for Hydrogeological Problems (I. M. Gor'kova and coworkers [4]), and for investigating peat in the Kalinin Peat Institute (M. P. Volarovich and coworkers [2, 33]). The apparatus is simple in design. It is being successfully used for studying the rheological properties of media whose properties are practically independent of stresses normal to the shear plane (paints, oils, etc.). Tolstoi's apparatus cannot be used for studying the rheological properties of soils, since the soils used as foundations of structures have quite a strong structural lattice. In order to impart a relative shear strain to the sample, it is necessary to apply considerable tangential stresses—of the order of $0.1-2 \mathrm{kg/cm}^2$, and sometimes even more. Such stresses can be imparted to the sample only if considerable friction forces exist between the plate A (Fig. 3) and the sample. It is obvious that in practice the light, freely supported plate cannot create friction forces of the order mentioned. Loading the plate is not feasible, since it flattens the sample. For the same reason the apparatus cannot be used to study the dependence of the rheological properties of a soil on stresses normal to the shear plane. Long-time tests are likewise impossible, since all four vertical faces of the sample are exposed. For samples with $h = 1-2$ cm and more* the strain will correspond to simple shear.

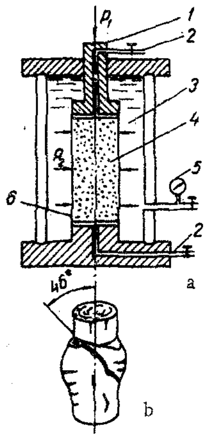

Fig. 2. Stabilometer: a) diagram of instrument (1—ram for transmitting load, 2—tube and values for creating open and closed systems, 3—hydrostatic pressure chamber, 4—sample, 5—manometer, 6—rubber tube); b) state of sample after testing for long-time strength.

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*For more on the open and closed systems see Section II.

*For clays of natural structure the height cannot be less than 1–2 cm for two reasons: 1) it is very difficult to cut such a sample from a monolithic block; 2) reducing the height of the sample sharply increases the experimental errors due to contact surface effects.

In fact, in the Tolstoi apparatus the tangential stresses are applied only on edges A, B. The other two edges C, D are free of tangential stresses. Accordingly, the rotational moment developed by the stress must be compensated by nonuniform pressure along the edges A and B. In the upper left and bottom right corners the pressure must be greater than the average, and in the upper right and bottom left corners less than the average. This was remarked upon by N. I. Malinin, who recommended loading the plate A [31]. These data show that in the Tolstoi apparatus the soil sample is in a nonuniform state of stress.

The Nikolaev apparatus, used by G. V. Sorokina [32] to study the rheological properties of muds, is a variant of the Tolstoi apparatus, based on the same principle.

4. **Plane-parallel shear apparatus.** This apparatus has been used to study the creep of clay soils (Fig. 4) by N. N. Maslov [8], R. Haefeli [12], and S. N. Sotnikov [7]. Abroad, it is called the Swedish Geotechnical Society's apparatus [24]. This instrument is better adapted than those previously described for rheological studies of solid uncracked clay soils.

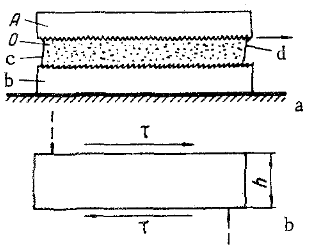

Fig. 3. Tolstoi's apparatus: a) diagram of apparatus (A and B—upper and lower plates, O—sample, C and D—edges); b) stress diagram. The broken-line arrows show the fictitious forces required to compensate the rotational moment.

However, in this instrument, as in Tolstoi's apparatus, the state of stress of the sample does not correspond to simple shear, since the rubber tube into which the sample is inserted cannot transmit tangential stresses over the cylindrical surface.

5. **Apparatus in which a hollow cylindrical sample is tested in torsion.** This apparatus is of considerable interest in relation to rheological studies [11, 25, 6, etc.]. From a theoretical standpoint it has very great advantages. In using it to test soils (Fig. 5) the chief difficulty is that to reduce the nonuniformity of the state of stress of the sample during the test the radii of the cylindrical surfaces bounding the sample must differ as little as possible. However, reducing the thickness of the sample increases the errors associated with the contact surfaces. Preparation of the samples for testing (especially for soils of natural structure) and the test method itself are very complicated. In twisting a hollow cylinder, as in the other apparatus previously described (§§ 1, 2), the strain may be concentrated in a narrow zone. Consequently, errors in determining the rheological parameters due to inaccurate determination of the relative strains are not excluded. A detailed analysis of possible variants of the apparatus for twisting hollow cylinders and possible loading conditions will be found in the paper by Whitman and Harkness [26].

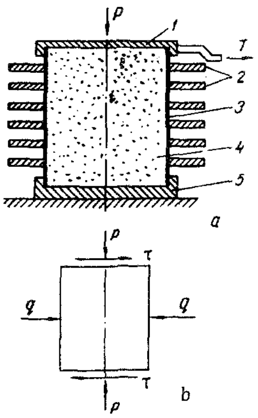

Fig. 4. Plane-parallel shear apparatus: a) diagram of apparatus, (1—moving ring, 2—rings to prevent sample from crushing, 3—rubber tube, 4—sample, 5—fixed ring); b) stress diagram.

6. **Simple shear apparatus.** This apparatus has been proposed and used for studying the rheological properties of soils by the authors and Professor G. M. Lomize [16, 17]. The design of this apparatus (Fig. 6) is ideally suited for studying soils with a lateral pressure coefficient close to unity (soils of most practical interest.) As the authros' experiments have shown, in this case the deformation of the sample is uniform and corresponds to simple shear.

The apparatus has the following advantages:

1. It makes it possible to study the dependence of the rheological properties of soils on the state of stress. Different states of stress are created by selecting corresponding stresses normal to the shear plane.

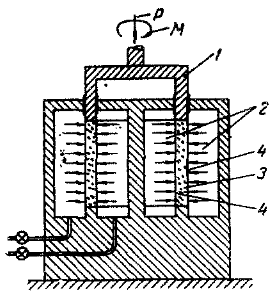

Fig. 5. Diagram of torsion apparatus: 1) working piston transmitting pressure and twisting moment, 2) chambers filled with liquid transmitting lateral pressure to the sample, 3) sample, 4) rubber tube.

2. It makes it possible to investigate the entire complex of strains during both loading and unloading: nominal-instantaneous, elastic, creep strains, etc.

3. Thanks to the use of an interferometer and an ordinary indicator the strains (and strain rates)

can be measured within wide limits—from 0.015 μ to 10 mm.

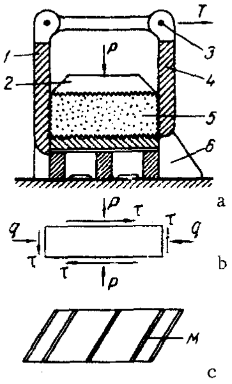

Fig. 6. Simple shear apparatus: a) diagram of apparatus (1 and 4—rear and front distorting walls, 2—plate transmitting pressure and tangential stresses, 3—hinges, 5—sample, 6—fixed base of apparatus); b) stress diagram; c) shape of sample after testing (M—chalk powder tracers).

4. The apparatus is suitable for long-time (more than a year) tests. For these purposes it is fitted with a special tank.

5. A strict check on volume strains can be kept during the test.

6. The progressive failure effect is excluded, together with the associated effects of forced change in the physical properties of the originally homogeneous sample. This is particularly important in long-time tests.

7. The method of preparing the samples for testing and the test method itself are simpler than in a stabilometer or a torsion apparatus.

The apparatus is only suitable for testing in the open system, which corresponds to the majority of practical problems.

7. **Roskoe apparatus.** This consists of a closed chamber in which the sample is subjected to compression, and then distorted in much the same way as in the simple shear apparatus [28]. The dimensions of the sample in plan are 6 x 6 cm, the height being 2 cm. However, as distinct from the simple shear apparatus, in Roskoe's apparatus the friction forces on the distorting walls are specially eliminated by introducing silicone oil into the gap between these walls and the rubber sheath surrounding the sample. The friction forces on the other two lateral faces, which in the Roskoe apparatus are made fixed, are eliminated in the same way. The state of stress of the sample in the Roskoe apparatus is the same as in the plane-parallel shear apparatus (Fig. 4). The absence of tangential stresses on the distorting walls creates a nonuniform distribution of tangential and normal stresses in the sample. To clarify the conditions in the deformed sample, Roskoe performed tests using contrast clay tracers. These tests confirmed the nonuniform deformation of the sample at small normal pressures, when "dragged-out zones" are distinctly observed.

II. OPEN AND CLOSED TEST SYSTEMS

The rheologist usually studies media whose physical properties remain almost unchanged during the experiment (suspensions, paints, bitumens, oils, etc.). In fact, in most cases the duration of the experiment is short. It is usual to assume that studies of the rheological properties of soils should also be conducted under conditions where the physical properties remain unchanged during the experiment. This condition is usually considered satisfied, if during the experiments the integrated moisture content of the sample does not vary. The other processes taking place in the sample began to be analyzed only recently.

Soils can be investigated by two different methods:

1. The integrated moisture content of the sample does not change during the experiment—closed test system.

2. The integrated moisture content of the sample does change during the experiment (decreases or increases)—open test system. Since in the closed system the integrated moisture content remains unchanged, such tests are considered most suitable for investigating the rheological properties of soils.

However, as established by the authors' experiments [17] and as follows from the literature data [20, 9, 18, 23, 15], in short-time, and particularly in long-time tests the physical state of the soil sample is liable to change in both open and closed systems.

In the closed system there can be no decrease in integrated porosity, but there may be redistribution of water, displacement and solution of trapped air, aggregation and dispersion of structural elements, transition of water from the bound to the state, and vice versa. Orientation of the particles, thixotropic processes, colloidal againg, etc. are established facts [1, 2, 4, 5, 9, 18].

In testing in the closed system it is necessary to distinguish two cases:

1. The sample undergoes uniform plastic deformation.

2. The sample undergoes nonuniform plastic deformation.

In the first case migration of moisture, salts, and microparticles will occur within small regions of soil. This is because when consolidation is completed the distribution of moisture in the sample is not ideally uniform, large and small pores exist in the soil. Uniform plastic deformation will be accompanied by equalization of the dimensions. Water will also be displaced to wet the new soil particles formed during dispersion In the case of coagulation structures shear deformation is accompanied by reorientation of the particles: there is a transition from a house-of-cards structure to a stacked structure [30, 14], which is more stable. Thus, even uniform plastic deformation leads to a change in the physical properties of the sample.

Nonuniform plastic deformation in a closed system also brings a redistribution of moisture, salts, microparticles, etc. between remote parts of the sample, where the intensity of plastic deformation is different.

The displacement of water, gas, salts, and microparticles and reorientation are processes that do not take place instantaneously, but require a certain, sometimes quite considerable time. As the displacement of moisture, salts, etc. proceeds and the sample passes into a state corresponding to the given regime of plastic deformation, the rate of these processes begins to decrease.

In the open system, apart from the processes characteristic of the closed system, there will be an exchange of water and salts between the deforming sample and the surrounding medium (studies at the Laboratory for Hydrogeological Problems, Gidroproekt, and foreign research). The intensity of this process will decrease, if the plastic deformation proceeds at nonincreasing rate.

The effect of the above factors on the rheological properties of soils has still only been superficially studied and it is not yet possible to characterize the phenomenon either from a quantitative or a qualitative viewpoint. However, it may be considered established that the plastic deformation of a cell is always associated with the transformation of the structure of the soil and the various processes accompanying this transformation. Therefore the choice of systems for testing soils in creep, long-time strength, etc. must depend on which system best reproduces actual conditions of operation of the soil in the foundations of structures. In natural conditions, over long periods, the action of the soil most nearly corresponds, in the overwhelming majority of cases, to the conditions of the "open system." The same conclusion was reached, in particular, by V. A. Florin on the basis of an analysis of the behavior of soils under different operating conditions [29].

SUMMARY

1. The instruments now being used to study the rheological properties of disperse systems with a low concentration of disperse phase are not suitable for investigating the rheological properties of soils, principally because they do not permit the determination of the dependence of the rheological characteristics on the state of stress.
2. The ordinary shear boxes and stabilometers widely used in soil mechanics are not satisfactory for studying the rheological properties of soils owing to the nonuniformity of the stress and strain field in the sample during testing.
3. The plane-parallel shear apparatus and Roskoe's apparatus are quite suitable for rheological research. However, the boundary conditions in these apparatuses do not correspond to the scheme of simple shear, since there are no tangential stresses on two sides of the sample.
4. From the theoretical viewpoint the best possibilities are afforded by an instrument in which a hollow cylindrical sample is tested in torsion. However, since a uniform stress and strain field in the sample is achieved only in testing a thin-walled cylinder, the advantages of the apparatus are much reduced by the conditions of experimental error, associated with the important role of boundary surface effects and the possibility of concentration of deformation in a narrow zone (which is attributable to the specific properties of soils), as well as by difficulties in preparing and testing the samples. This limits the area of usefulness of the apparatus to special types of investigation.
5. In any test system the properties of the sample vary during the process of plastic deformation. To a considerable extent, the open system simulates the changes that take place in foundation soils.
6. It is recommended that studies of soils and other materials whose rheological properties depend not only on the tangential but also on the normal stresses be carried out on a simple shear apparatus.

REFERENCES

1. P. A. Rebinder, Proceedings of the Conference on the Engineering-Geological Properties of Soils and Methods of Studying Them [in Russian], I, Moscow, 1956.
2. M. P. Volarovich, I. I. Lishtvan, and V. M. Naumovich, IFZh, 5, no. 2, 1962.
3. S. S. Vyalov et al., Strength and Creep of Frozen Soils [in Russian], Izd-vo AN SSSR, 1962.
4. I. M. Gor'kova, Kolloidn. zh., 20, no. 5, 1958.
5. T. Yu. Lyubimova, R. A. Agapova, Kolloidn. zh., 24, no. 1, 1962.
6. S. R. Meschan, Izv. AN Arm. SSR, Fiz.-mat. nauk, 15, no. 2, 1962.
7. S. N. Sotnikov, "Laws of development of creep strains in clay soils under shear," Scientific Communication from the Leningrad Institute of Structural Engineering, Leningrad, 1960.
8. N. N. Maslov, Materials of a Conference on the Problems of Studying Landslides and Preventive Measures Against Them [in Russian], Izd. Kievskogo un-ta, 1964.
9. M. N. Gol'dshtein, S. S. Babitskaya, Osnovaniya, fundamenty i mekhanika gruntov, no. 4, 1959.
10. B. F. Rel'tov, Materials of a Conference on the Problems of Studying Landslides and Preventive Measures Against Them [in Russian], Izd. Kievskogo un-ta, 1964.
11. E. C. W. A. Geuse, Tan Tjong-Kie, Proc. of the Second Intern. Congress on Rheology, London, 1954.
12. R. Haefeli, Wasser und Energiewirtschaft, 46, no. 3, Zürich, 1954.
13. S. Murayama and T. Shibata, Proc. V. Intern. Conf. Soil Mechanic and Found. Eng., 1, Paris, 1961.
14. D. Trollope, Chan. Proc. Amer. Soc. Civ. Engrs., 86, pt. 1, NSM2, 1960.
15. M. Hvorslev, Proc. ASCE Research Conf. on Soils USA, 1960.
16. G. M. Lomize, A. M. Gutkin, and N. V. Zhukov, IFZh, 5, no. 6, 1962.

17. G. M. Lomize, A. M. Gutkin, and N. V. Zhukov, Osnovaniya, Fundamenty i mekhanika gruntov, no. 2, 1963.

18. V. S. Fadeeva, Kolloidn. zh., 19, no. 5, 1957.

19. K. Terzaghi and R. B. Peck, Soil Mechanics in Engineering Practice [Russian translation], Gosstroiizdat, 1958.

20. A. N. Zelenin, G. M. Lomize, V Conf. Soil Mech. and Found. Eng. [Russian translation], Gosstroiizdat, 1961.

21. Research Conf. on Shear Strength of Cohesive Soils USA, 1960.

22. A. Ya. Turovskaya, "Effect of deformation on the structure of clay soils," Scientific Communication no. 6 [in Russian], Dnepropetrovsk Institute of Railroad Transportation Engineers, 1957.

23. A. Bishop and D. Henkel, Measurement of Soil Properties in Triaxial Tests [Russian translation], Gosstroiizdat, Moscow, 1961.

24. A. Kerdi, Talajmechanika, 1, 1952.

25. A. Baudran and C. Duplus, Transactions of the Brit. Ceram. Soc., 58, no. 7–8, 1959.

26. R. Whitman, and Harkness. Mass. Inst. of Technol., Soil Eng. Divisions, October, 1958.

27. P. Bridgman, Studies in Large Plastic Flow and Fracture [Russian translation], IL, 1955.

28. R. Roskoe, Proc. 3. Int. Conf. Soil Mech, and Found, Eng., 1, 1953.

29. V. A. Florin, Fundamentals of Soil Mechanics, 1, 2 [in Russian], Gosstrolizdat, Leningrad-Moscow, 1959–61.

30. Ya. L. Kogan, V. A. Iosilevich, Osnovaniya, fundamenty i mekhanika gruntov, nos. 2 and 5, 1961.

31. M. P. Volarovich, N. I. Malinin, Kolloidn. zh., 20, no. 3, 1958.

32. G. V. Sorokina, Tr. NII osnovanii i podzemnykh sooruzhenii, coll. 33, Gosstroiizdat, Moscow, 1958.

33. M. P. Volarovich, Kolloidn. zh., 16, no. 2, 1954.

28 May 1965

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