Comparative analysis of stability of embankment on the basis of torsional ring shear test

E S Sobolev¹ and D S Morev²

¹Department "Soil mechanics and geotechnics", Moscow State University of Civil Engineering (National Research University), 26, Yaroslavskoye Shosse, Moscow 129337, Russia
²Research and Educational Center "Geotechnics", Moscow State University of Civil Engineering (National Research University), 26, Yaroslavskoye Shosse, Moscow 129337, Russia

E-mail: e.s.sobolev@mail.ru

Abstract. Designing slopes and embankments is an important geotechnical stage in the framework of industrial, civil and transport construction. For analytical and numerical stability calculations for the first limiting state, soil strength parameters are required, obtained, as a rule, based on the results of field and laboratory studies. Currently, a significant number of methods and equipment for soil testing for shear have been developed. In this paper we focus on the method of testing of cohesive soils under torsional shear ring. It is believed that this type of shear tests most accurately repeats the mechanical process observed during the destruction of slopes and embankments with the formation of fixed cut surfaces and taking into account large shear deformations. This paper contains information on the design of an experimental instrument for a ring (cylindrical) shear of cohesive soil samples. The processing of the results of torsional shear with different speeds is presented, the parameters and methods for finding them. The main purpose of the tests - determination of residual strength parameters: the angle of internal friction and cohesion. Examples are given of using the parameters obtained during tests of a torsional shear for numerical simulation of embankment from cohesive soil.

1. Introduction

Tests in the conditions of an annular (or cylindrical) shear of soil samples are carried out in order to determine the parameters of residual strength: internal friction $\varphi_r$ and cohesion $c_r$.

The parameters of residual strength $\varphi_r$ and $c_r$ are used in calculating the stability of man-made embankments, natural slopes, slopes of pits, retaining walls and other structures. The values of these parameters are determined in laboratory conditions for large values of shear deformations, assuming that this corresponds to the mechanism of shear of the soil mass in natural conditions. Especially when part of the soil mass was already in a state of limitation and a repeated shift occurs along the formed sliding surface.

Many authors [1-5] note that when determining the values of the parameters of residual strength, not only the magnitude of the normal pressure in the shear plane, but also the shear rate plays a significant role. Usually, when the slopes are shifted, the observed speed of their movement can vary from 5 cm/year to 50 cm/day. Given this circumstance, subsequent laboratory tests were carried out with different rates of deformation.
Determination of residual strength using ring shear instruments is included in BS 1377-7: 1990 standards «Methods of soils for civil engineering purposes. Shear strength tests (total stress)» and ASTM D6467 - 13e1 «Standard test method for torsional ring shear soothing». To date, this test method is not regulated by regulatory documents in the territory of the Russian Federation. One of the first annular shear device structures has been developed in Russia G. Pokrovsky [6]. The first definition of the residual strength of soils with a natural structure in drained conditions was made by B. Tiedemann [7].

The torsional ring shear test method is recommended for use in the practice of geotechnical laboratories.

2. Laboratory tests
For testing torsional shear was applied experimental apparatus kinematic torsional shear, combined with control equipment, includes a set of pneumatic load device 10 kN, the control blocks and a personal computer equipped with software.

The equipment used allows testing according to the kinematic torsional shear pattern with measurement of vertical and horizontal force.

An experimental setup implements a torsional single-plane cut of hollow (annular) and solid samples. In this case, the lower cage is rotated at a given speed (kinematic mode), and the shear resistance is measured using a force sensor connected with a lever to the upper casing. The sample is hooked by means of rings with blades located in the upper and lower holder.

The tests were carried out according to a consolidated-drained scheme. Testing of ring specimens are more accurate, since they allow more precise control of the stress state during the cutting process, however, it was not possible to manufacture such specimens for the given physical characteristics of the soil, due to which continuous cylindrical specimens were tested.

The tests of the torsional section were carried out on artificially made samples of man-made powdered-clay soil according to GOST 30416-2012 of a given particle size distribution, with a density of addition of 2.320-2.360 g/cm³ and a moisture content of 11 ... 13%. Fractions larger than 2 mm were excluded.

Before testing, the samples were pre-compacted to stabilize the vertical deformation. The precompaction pressure was 200, 400, 800 kPa. After loading the samples into the shear device and holding for 30 minutes, a kinematic cut was started at a rate of 0.004 mm/min (0.0069 °/min) and also at a rate of 0.978 mm/min (1.6875 °/min). These values corresponded to the maximum and minimum possible cutting speeds in this device design. At the same time, the minimum speed was taken as the closest to the actual speed of the embankment of man-made soil, determined during field observations. The tests were carried out until the angle of rotation reached 70 °.

Processing of the results to determine the parameters of the residual shear resistance \( \varphi_r, c_r \) was performed by analogy with GOST 12248-2010. According to the test results, the tangential and normal stresses \( \tau \) and \( c \), MPa were calculated using the formulas:

\[
\tau = 3 \frac{F_2 L}{2 \pi R_z} \quad (1)
\]

where \( \tau \) is the rotational shear resistance, in MPa; \( F_2 \) is the reading of the torque sensor, in N; \( R_z \) is the outer radius of the sample, in mm; \( L \) – shoulder torque, in mm.

\[
\sigma = \frac{F_1}{\pi R_z} \quad (2)
\]

where \( \sigma \) is the vertical stress, in MPa; \( F_1 \) – normal vertical force acting on the sample, in N.

The parameters of the residual resistance to shear \( \varphi_r, c_r \) were determined as parameters of linear dependence on the basis of the Coulomb law:
\[
\tau = \sigma \tan \varphi_c + c_r,
\]
where \(\tau\) is the residual shear resistance, in MPa; \(\varphi_c\), \(c_r\) – the residual value of the angle of internal friction and specific cohesion, respectively.

As a result of processing the test results, the dependences of the shear resistance on the displacement and the residual shear resistance values obtained in fig. 1 and 2.

Figure 1. Experimental dependences of shear stresses \(\tau\) (kPa) on the angle of rotation \(\alpha\) (º) (a) and normal stresses \(\sigma\) (kPa) (b) obtained at a constant shear rate of 0.004 mm/min (0.0069 º/min).

Figure 2. Experimental dependences of shear stresses \(\tau\) (kPa) on the angle of rotation \(\alpha\) (º) (a) and normal stresses \(\sigma\) (kPa) (b) obtained at a constant shear rate of 0.978 mm/min (1.6875 º/min).

3. Numerical simulation
Simulation of embankment stability in spatial formulation was performed in the specialized geotechnical software complex PLAXIS 3D v. 2017.1. For the calculations, a model was used having a length of 60 m, a width of 1 m and a thickness of underlying soils with a capacity of 10 m. The height of the embankment was assumed to be 4 m. The Mohr – Coulomb elastic-plastic model was used as a computational soil model. The parameters of the soils used in the calculations were taken on
the basis of laboratory studies of the embankment soils (Fig. 1 and 2). In addition to the torsional shear tests, triaxial soil test data were used (Poisson's ratio $\nu$, 0.05; Young's modulus $E$, 38.9 MPa).

The calculations were performed on the same model with two possible sets of properties. The first option was to use the strength parameters obtained from the results of the «fast» torsional cut at a speed of 1.688 °/min (Fig. 3a). The second option is a «slow» torsional slice with a speed of 0.006 °/min (Fig. 3b).

Figure 3. General view of the formed sliding surface from the results of numerical calculations in the PLAXIS 3D software package. Total displacement of the slope of the embankment, $10^{-3}$ m. In the calculation used the parameters of residual strength obtained at a speed of torsional shear 1.688 °/min (a) and 0.006 °/min (b).
As a result of the calculations, the possible shapes of the sliding surfaces were presented, shown in figure 3, as well as the reserves of the stability coefficient of the designed embankment from man-made soil.

As a result of the calculations, it was found that for the first option, the «fast» torsional shear, the stability factor was $M_s = 1.9$ (which is more than the maximum permissible value $M_{s, \text{max}} = 1.9$). For the second variant, an even greater margin of stability coefficient $M_{s, \text{2}} = 3.3$ was obtained.

4. Results and conclusions

Based on laboratory tests performed cohesive soil man-made torsional shear method with different velocities and mathematical modeling FEM embankment stability problem based on the obtained in laboratory studies soil properties can draw the following conclusions:

1. Studies of clay soils, performed earlier [8–12], show that residual shear strength is mobilized at the first signs of embankment destruction. Tests with a fast cut-off speed do not allow adhesion forces to be realized for samples of cohesive soil prepared from samples of an impaired structure with fully specified humidity. Tests with a slow cutting speed show that for a long period of time that tests will continue (more than one week), adhesion forces can be realized, which significantly increases the strength properties of such a soil.

2. In the process of long-term tests there is a significant loss of soil samples given by the humidity specified at the beginning of the tests. If initially the samples had a moisture content of 12%, then after a week of long-term tests, their moisture content did not exceed 8%, which corresponds to the transition of this cohesive clay soil from plastic to solid state. To eliminate this drawback, it is necessary to improve the design of the torsional slice device and adapt it to the tests in a consolidated undrained mode, as, for example, in [13–15].

3. Numerical modeling of the stability of the embankment of man-made cohesive soil, taking into account laboratory data using the method of torsional slice, shows that when using the parameters of the strength of the slow slice, there is a much larger margin of stability of the embankment than when using the results of the rapid shear. Studies by various authors [16–21] show that in order to choose the rate of deformation of samples, one should be guided, first of all, from the results of observations of real slopes and embankments that are in the limiting state.

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