In-Situ Determination of the Rheological Characteristics of Soils on Slopes

Mesure *in situ* des caractéristiques rhéologiques des sols en pente

G. TER-STEPANIAN, *Professor, Head of the Laboratory of Soil Mechanics and Engineering Geology, Geological Institute, Armenian Academy of Sciences, Erevan, Armenia, U.S.S.R.*

SUMMARY

Open and closed depth creep wells are made on landslide slopes for the investigation of deformations at depth. Long-term observations of the depth creep of slopes permit the determination of the rheological characteristics of soils, the limit of plastic flow, and the coefficient of viscosity of soils *in situ*. These observations are free of space and time limitations caused by the small dimensions of the samples and the short duration of the tests in laboratory investigations. The corresponding formulae for calculation of these rheological characteristics are derived. Two examples of such calculations are given, based on the observations made in depth creep wells on landslide slopes of the Black Sea coast of the Caucasus.

SOMMAIRE

On décrit dans cet exposé la construction de puits ouverts et de puits fermés qui furent installés dans des pentes de glissement de terrain pour étudier le fluage du sol en profondeur. L'auteur démontre la possibilité de déterminer les caractéristiques rhéologiques importantes du sol, la limite du fluage plastique et le coefficient de viscosité du sol, d'après les résultats des observations à longue durée des déformations du sol en profondeur. Ces observations sont libres des restrictions des travaux de laboratoire liés aux dimensions restreintes d'échantillons et à la courte durée des essais. Des formules correspondantes et des exemples de calcul sont donnés d'après les résultats des observations du fluage en profondeur effectuées dans deux puits implantés dans des pentes de glissement sur la côte de la mer Noire du Caucase.

THE METHOD for determining the average shearing resistance of soils on the basis of slide data which permits one to find out the strength characteristics of soil *in situ* is well known in geotechnics (Terzaghi and Peck, 1948). Similarly, a method for determining other average rheological characteristics of soil on slopes on the basis of depth creep data may be suggested. These characteristics are the limit of plastic flow and the coefficient of viscosity of the soil.

In both of these cases, the determination of soil characteristics is free of the limitations involved in laboratory investigations due to the method of sampling, to the scale effect, and to the impossibility of modeling natural geological and hydrological conditions; in other words, it is free of space limitations. Determination of rheological characteristics of soils based on the long-term observations of depth creep of slopes has an additional advantage in comparison with

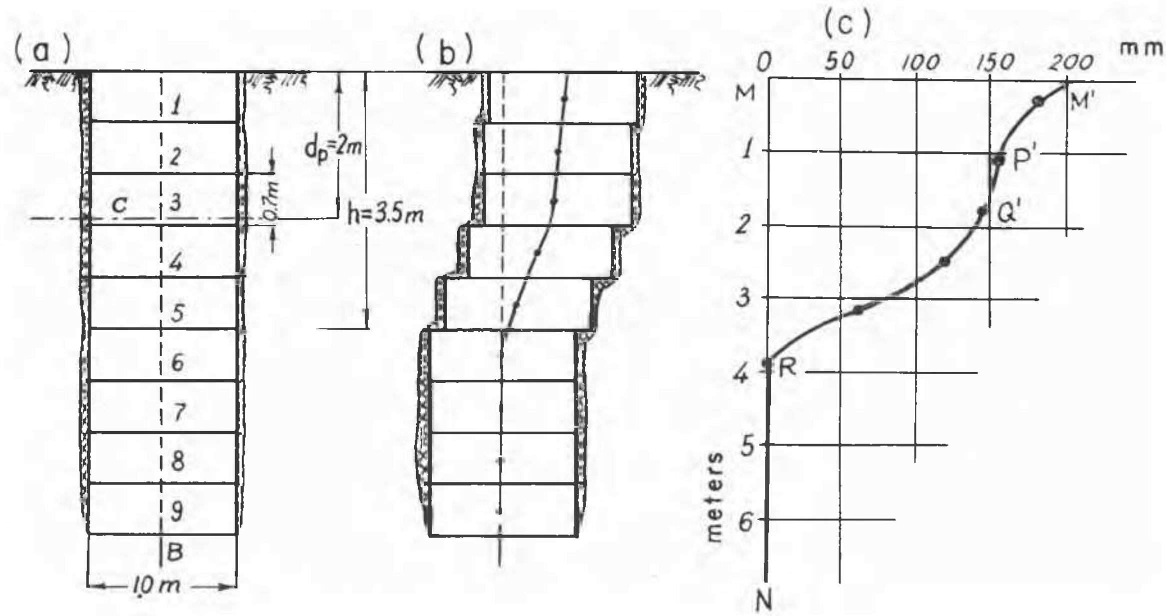

FIG. 1. Open depth creep well: (a) before the deformation of soil; (b) after deformation; (c) deformation in open well No. 3.

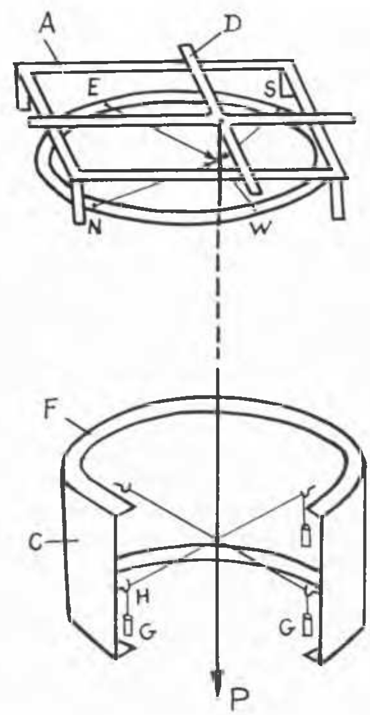

FIG. 2. Measurement of horizontal displacement of a cylinder in open well.

laboratory investigations, which necessarily are of short duration. This may be denoted as the freedom from time limitations.

Depth creep wells are used for the observation of deformations in the soil mass. Two types of depth creep wells are used, open and closed. An open depth creep well is a shaft about 1.0 m in diameter. Its lining consists of separate metal cylinders (C) 0.5 to 0.7 m high, with inner flanges. Bolted cylinders are sunk as open caissons. When the driving reaches desired depth (which is usually bed rock) the cylinders are disconnected and sealed by the soil (Fig. 1a). Thus the cylinders can move freely with the neighbouring soil in a horizontal direction. A benchmark (B) is driven in the bottom of the shaft.

Each cylinder has four hooks (H) placed in the middle of the cylinders (Fig. 2). On hooks, two nylon threads with weights (G) are hung; their crossing point is the centre of the cylinder. A frame (A) is installed on the earth surface. On the frame a cross-shaped piece (D) with a plumb (P) can move freely. Bringing this plumb in contact with the centres of successive cylinders, the distances are measured between the plumb line and each of the four marks N, S, E, and W made on the upper flange of the top cylinder. Graphically levelling these four distances, the positions of the centres of each cylinder are found (Fig. 1b). Observations on the open depth creep wells are repeated periodically and corresponding diagrams are plotted.

A closed depth creep well is a borehole filled with short wooden blocks of corresponding diameter, or chocked up with poor concrete, broken brick etc. After some time a shaft is dug beside the closed depth well and the displacement of the blocks is determined. Thus each closed depth creep well can serve for only one determination.

Two rheological characteristics of soils—the limiting value of the coefficient of mobilized shear strength $\tan\theta_0$, and the coefficient of flow, λ, may be determined on the basis of observations made on the depth creep wells. These characteristics are connected with the limit of plastic flow, τ_0, and the coefficient of viscosity, η, of the soil by the following expressions:

$$\tan\theta_0 = \tau_0/(H + \sigma'), \tag{1}$$

and

$$\lambda = (H + \sigma')/\eta, \tag{2}$$

where $H = c' \cot\phi'$ is the tension intercept or the complete traction resistance in terms of effective stresses σ' (Ter-Stepanian, 1963).

Planar depth creep of slopes occurs when the layer of soil having a uniform thickness, h, is located on the inclined surface of contact with the underlying rocks. The described method for determining the rheological characteristics is applicable in two cases: (1) when a uniformly distributed load with intensity, q_0, caused by the weight of a layer of stiff stratum acts on the surface of soil investigated; (2) when the surface of soil is free of surcharge ($q_0 = 0$). Equations necessary for the analysis of the planar depth creep were given previously (Ter-Stepanian, 1963); they are presented here in revised form.

(*a*) The relation between the depth, d_r, of the rigidity zone and limiting value, $\tan\theta_0$, of the coefficient of mobilized shear strength

$$\tan\theta_0 = \frac{(q_0 + \gamma d_r)\tan\beta}{\dfrac{H}{\cos^2\beta} + q_0 + \gamma_w d_p + \gamma' d_r} \tag{3}$$

where γ = unit weight of soil, γ' = unit weight of submerged soil, γ_w = unit weight of water, d_p = depth of groundwater table, β = angle of inclination of the slope.

(*b*) The equation of the rate of depth creep, v_z, of a layer of soil, located at the depth z from the surface of soil.

$$v_z = \lambda\cos\beta\left[A(h - z) + B\log_e\left(1 - \frac{\gamma'(h - z)}{C}\right)\right] \tag{4}$$

where

$$A = (\gamma/\gamma')\tan\beta - \tan\theta_0, \tag{5}$$

$$B = [\tan\beta/\gamma'][(\gamma/\gamma')C - q_0 - \gamma h], \tag{6}$$

$$C = (H/\cos^2\beta) + q_0 + \gamma' h + \gamma_w d_p. \tag{7}$$

Vertical lines deform and take a complicated configuration as a result of the depth creep of slopes. If the deformations of the slope do not pass into the plasticity phase (shear), the vertical line MN on Fig. 1c transforms after deformation into the line M′N which consists of the following parts: (1) curvilinear section M′P in the zone of surface creep; (2) vertical section P′Q′ in the zone of rigid displacement; (3) curvilinear section Q′R in the zone of depth creep; and (4) vertical section RN in immobile rocks.

If the deformations of the slope pass into the plasticity phase (shear), a section R′R, (Fig. 3) practically parallel to the slope, is added to the above-mentioned elements of deformed line. This section is located in the plasticity zone along the surface of sliding. Deformations in this zone considerably exceed the deformations in both the zones of depth and surface creep.

The inclination of the deformed line within the zone of depth creep depends on the viscosity of soil. The values of

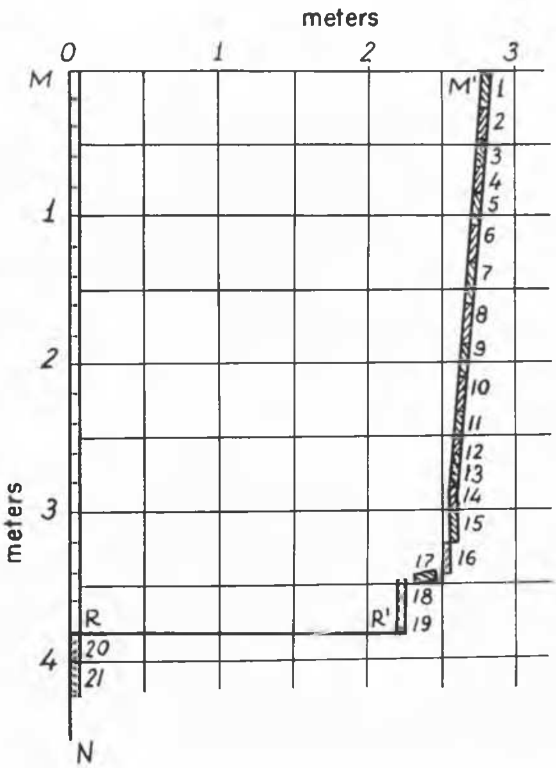

FIG. 3. Closed depth creep well No. 17 after deformation.

displacements, s_1 and s_2, of two points located within the zone of depth creep on the depth z_1, and z_2, in time interval t, are $s_1 = v_1 t$ and $s_2 = v_2 t$, where v_i is the rate of depth creep (Eq 4). Hence we derive:

$$\lambda = \frac{1}{t \cos \beta} \cdot \frac{s_1 - s_2}{A(z_2 - z_1) + B \log_e \left[\frac{C - \gamma'(h - z_1)}{C - \gamma'(h - z_2)} \right]} \qquad (8)$$

Values of tan θ_0 and λ (Eqs 3 and 8) for the whole soil layer may be determined based on field measurements and laboratory tests. This permits the determination of the rheological characteristics (τ_0 and η) for soil located at any depth (Eqs 1 and 2).

As an example of the determination of rheological characteristics, the results of measurements of displacements of two depth creep wells are used; these wells were set on a landslide slope on the Caucasus coast of the Black Sea. The slope body is composed of inclined layers of gray argillites and sandstones of Oligocene, dipping parallel to the slope and covered by the products of weathering. The groundwater is on the contact of weathered clays with rocks. The planar landslides and earth flows proceed along this contact.

An open depth creep well was made in Sochi on November 20, 1960; the next measurement was taken on June 10, 1962, i.e. with the time interval, $t = 4.9 \times 10^7$ sec. The slope is described by the following values: $h = 3.50$ m, $\beta = 23°$, $d_p = 2.0$ m, and $d_r = 1.40$ m. The soil has the following properties: $\gamma = 2.04$ tons/cu.m., $c' = 4$ tons/sq.m., $\phi' = 21°10'$.

The displacement of the centre of cylinder No. 3, at the depth $z_1 = 1.75$ m was 146 mm, and that of the cylinder No. 5, at the depth $z_2 = 3.15$ m was 60 mm (Fig. 1c). Using Eqs 3 and 8, tan $\theta_0 = 0.077$ and $\lambda = 2.38 \times 10^{-8}$ sec.$^{-1}$. Using Eqs 1 and 2 for the soil located at the depth $z = 3.0$ m ($\sigma' = 0.51$ kg/sq.cm.) the following rheological characteristics are found: $\tau_0 = 0.12$ kg/sq.cm. and $\eta = 6.5 \times 10^7$ kg-sec/sq.cm.

A closed depth creep well was made in Khosta on December 31, 1955, and opened December 7, 1962, i.e. after almost 7 years. The time interval $t = 2.18 \times 10^8$ sec. The slope is described by the following values: $h = 3.8$ m, $\beta = 10°$, $d_p = 0$, and $d_r = 1.0$ m. The soil properties are: $\gamma = 1.96$ tons/cu.m., $c' = 2.3$ tons/sq.m. and $\phi = 15°$.

The displacement of wooden block No. 5, at the depth $z_1 = 1.0$ m was 2.70 m and that of block No. 15, at the depth $z_2 = 3.1$ m was 2.55 m. Hence tan $\theta_0 = 0.035$ and $\lambda = 1.13 \times 10^{-8}$ sec^{-1}. For the soil at the depth 3 m ($\sigma = 0.29$ kg/sq.cm.) it was found that $\tau_0 = 0.04$ kg/sq.cm. and $\eta = 1.0 \times 10^8$ kg-sec/sq.cm.

The displacement of the top block of well No. 17 in the course of 7 years was 2.80 m. Fig. 3 shows that to the creep depth, which was shown in the inclination of the well (Block Nos. 1 to 16), a considerably larger deformation of shear in the plasticity zone was added as expressed by the displacement of soil on the boundary between Blocks 19 and 20 (line RR').

These values of the coefficient of viscosity are to be considered as average ones, obtained with the assumption that the depth creep of slopes takes place at a constant rate. In reality, the slope deformation proceeds at a variable rate, accelerating in the wet periods of the year and decelerating in the dry ones; it is natural that the values of the coefficient of viscosity alter correspondingly. Increasing the frequency of observations and raising their exactness provides a closer relationship among the factors involved. Nevertheless, the results of field determinations of rheological characteristics are nearer to the reality than the data obtained in laboratory investigations.

REFERENCES

TER-STEPANIAN, G. (1963). On the long-term stability of slopes. Norwegian Geotechnical Institute, *Publ. No. 52.*

TERZAGHI, K., and R. PECK (1948). *Soil mechanics in engineering practice.* New York, Wiley.