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Determination of the initial soil stress state

Détermination de l'état initial des contraintes du sol

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SYNOPSIS The determination of the initial stress state of the soil massif is of major importance, because its reliability governs the forecasting of the stress and strain redistribution due to external effects. Several methods are presented, tested in MCEI and UACE, for the determination of the initial stress state of the soil massif by using: a) soil dynamometers and boreholes, b) soil dynamometers and trenches, c) three-stage dynamometers, d) laboratory method. The results are also presented. Equations are given for calculating the full tensor of stresses in the soil massif in semi-infinite space and in natural and artificial slopes.

The initial (natural) stress state of the soil massif is one of the important considerations of Applied Geomechanics. Classical Mechanics usually treats problems of artificial and homogeneous media, where there is no initial stress state or the stress state is known, but Applied Geomechanics treats problems, where the initial stress state of the soil massif is unknown.

As shown by Ter-Martirosyan, Ahpatelov (1982) and Stefanoff, Jellev (1980), the reliability of the initial stress state in many cases governs the forecasting of stress and strain redistribution in the soil massif, due to engineering activity. Taking into consideration the initial stress state of the soil massif is important also for the determination of the mechanical characteristics (strain and strength) of the soil. The initial stress state affects also the slope stability in excavations.

It should be noted that the importance of the initial stress state of the soil massif has until now been neglected. This is so, because the basic problems of soil mechanics are solved by assuming a linear stress distribution caused by additional external effects, where the initial stress state does not affect the stress distribution, and therefore it is not necessary to know it. As shown by Ter-Martirosyan, Ahpatelov (1982), even if the linear strain is neglected, there is a full class of problems in Applied Geomechanics, where the initial stress state is decisive. These problems are connected with the variation of the soil massif configuration caused by certain engineering activity.

Recently many methods have been proposed for the determination of the initial stress state of the soil massif.

Generally vertical stresses σ_z are determined by the weight of overlaying layers, i.e. by the equation:

$$\sigma_z = \sigma_\gamma = \sum_{i=1}^{n} \gamma_i h_i, \qquad (1)$$

where: σ_γ - overburden pressure,
γ_i - unit weight of the i-th soil layer,
h_i - thickness of the i-th soil layer.

Soil dynamometers inserted in the massif are used to determine the horizontal stress σ_x. While the determination of vertical stress σ_z does not cause specific objections, the same cannot be said for the determination of horizontal stress σ_x. It is known that each body different from the soil, when inserted into it causes concentrated stresses (degeneration of the stress state). So that even after relaxation of the stress the readings of the soil dynamometer shall not correspond to the measured horizontal stress $\sigma_{x,m}$, i.e.:

$$\sigma_{x,m} = \sigma_x + \Delta\sigma, \qquad (2)$$

Considering the soil as a medium subjected to the theory of hereditary creeping with age, Kyatov (1983) derived an equation for the additional stress $\Delta\sigma$, varying with time due to relaxation, as follows:

a) at the moment of final insertion of the dynamometer:

$$\Delta\sigma = \frac{\nu\delta E_{o,l}}{2(1-\nu^2)lb}\left\{t_o - \frac{1}{\eta_l}\left(1-\frac{E_{o,l}}{E_o}\right)\left[\exp\left(-\eta_l\frac{E_o}{E_{o,l}}\,t_o\right)-1\right]\right\} \qquad (3)$$

b) after stabilization of stress:

$$\Delta\sigma_{(t_\infty)} = \Delta\sigma_{(t_o)}\frac{E_{o,l}}{E_o}, \qquad (4)$$

where:

t_o - time of insertion of the dynamometer,
v - speed of insertion,
l - length of the dynamometer,
δ - thickness of the dynamometer,
b - width of the dynamometer,
E_o - initial (instant) modulus of total strain,
$E_{o,l}$ -long-term modulus of total strain.

On the basis of these equations, Kyatov (1983) proposed a method to determine the coefficient of initial earth pressure at rest K_o.

Another method, using soil dynamometers, is proposed by Ahpatelov and al. (1984). The conception of this method is to use the initial stress state of the soil massif as a force field causing strain and stress in the soil and to register them. This is conducted as follows. Soil dynamometers are inserted in the soil massif, characterized by initial stress state $\sigma_z^o = \gamma z$, $\sigma_x^o = \sigma_y^o = K_o \gamma z$; $\tau_{xy}^o = \tau_{yz}^o = \tau_{zx}^o = 0$. Then we wait for stabilization after relaxation. The stresses shall be equal to the sum of $\sigma_x^o = \sigma_y^o$ and additional $\Delta\sigma$. A deep borehole is drilled with a radius r_o at a distance r from the soil dynamometer. In this case the readings of the soil dynamometer are different, and it can convincingly be confirmed, that the value of the difference σ is caused by the redistribution of the initial horizontal stress, but the value of $\Delta\sigma$ shall remain as before. After that, comparing $\bar{\sigma}$ and the additional stress, σ_x^+ caused by the borehole and calculated as a function of the coefficient K_o, we can judge for the value of the latter. So, for example in a deep borehole (in cylindrical coordinates):

$$\sigma_r = \gamma z\ (1 - r_o^2 / r^2) K_o, \tag{5}$$

$$\sigma_r^+ = \sigma_r^o - \sigma_r = \sigma_x^o - \sigma_r = \gamma z\, K_o r_o^2 / r^2 = \bar{\sigma}_r = \bar{\sigma}_x, \tag{6}$$

from where:

$$K_o = \bar{\sigma}_x r^2 / \gamma z r_o^2\ , \tag{7}$$

After determining $\bar{\sigma}$ from the difference in the readings of the soil dynamometer and the unit weight of the soil, it is easy to calculate the value of K_o for the soil massif.

The practical use of boreholes is hindered by the quick attenuation of the additional stress, when the distance between the axis of the borehole and the dynamometer is increased. In such case the different readings give only the error of measurement. Therefore it is acepted to use a longitudinal trench instead of a borehole. The soil dynamometers are inserted along the axis of the future trench. For the attenuation coefficient α_r Ter-Martirosyan and al. (1984) have prepared tables related to the depth of insertion of the dynamometer z, the depth and width of the trench, for the cases K_o=0 and K_o=1. The values of α_r in these tables are recommended for the central axis of a symmetrical trench with slopes 25° to 50°. Under these conditions:

$$\sigma_x^+ = \alpha_r \cdot \gamma z \tag{8}$$

and the coefficient K_o is calculated after the equation:

$$K_o = (\sigma_{x,o}^+ - \bar{\sigma}_{x,1}) / (\sigma_{x,o}^+ - \sigma_{x,1}^+), \tag{9}$$

where: $\sigma_{x,o}^+$ and $\sigma_{x,1}^+$ are the calculated values for the additional horizontal stress respectively for K_o=0 and K_o=1. A methodical experiment has been carried out for determing K_o according to the described method in a homogeneous massif of loam with a trench 4x4x30m. The value obtained for K_o is 0.88. The above methods permit the determination of the initial stress state of a soil massif as a semi-infinite space, but they are not adapted for the determination of the initial stress state of the soil in natural and artificial slopes. Therefore a method has been developed, which eliminates this defect.

The method is based on the assumptions which are used in equations (2), (3) and (4). From equations (3) and (4) it follows that for δ=0:

$$\Delta\sigma(t_o) = \Delta\sigma(t_\infty) = \Delta\sigma = 0. \tag{10}$$

Then from (2) follows:

$$\sigma_m = \sigma_x, \tag{11}$$

i.e. the measured stress is equal to the natural stress. It is not possible to construct a soil dynamometer with zero thickness, but we can obtain the experimental relationship:

$$\sigma_m = f\ (\delta) \tag{12}$$

and to extrapolate for δ=0. Then

$$\sigma_m(\delta_o) \approx \sigma_x. \tag{13}$$

To obtain the above relation, a three-stage soil dynamometer has been constructed (Fig.1).

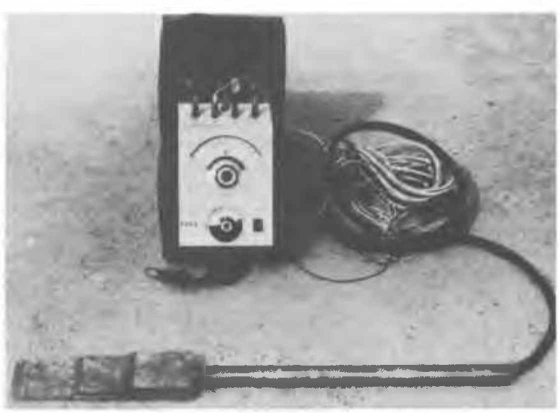

Fig. 1 General view of the three-stage soil dynamometer

It represents a stepped rigid metal plate 1 with three thicknesses (Fig. 2).

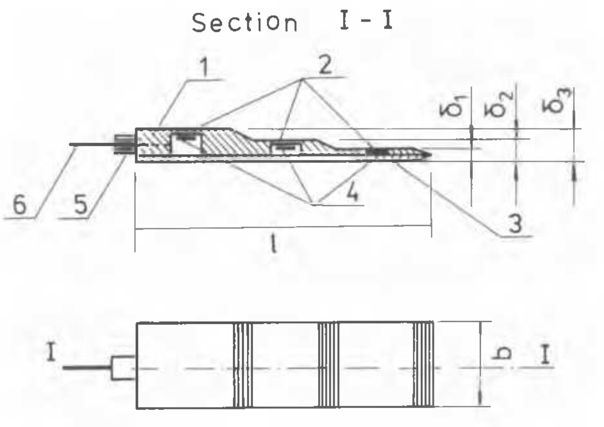

Fig. 2 Scheme of the three-stage soil dynamometer, 1-stepped metal plate; 2-diaphragm; 3-cover; 4-tensoresistors; 5-adaptor for fitting the drilling rod; 6-conductor.

The transition between the different thicknesses is with a slope n:l. Symmetrically in each step are formed diaphragms 2 with a fixed thickness and diameter and tensoresistors 4 fitted to them. The openings for the diaphragms are closed by a rigid metal cover 3.In order to increase the sensitivity of measuring the deformations of the diaphragms, a full bridge scheme of connecting the tensoresistors in each diaphragm has been used.

The interaction of the three-stage dynamometer with the soil had been investigated in a calibrating device (Jellev, 1977) under the conditions of a homogeneous stress state and in a soil base loaded by a rigid slab under the conditions of a nonhomogeneous stress state,which is known.

Experimentally it has been proved that equation (12) is a linear function under the conditions of a homogeneous stress state, but under a nonhomogeneous stress state it is not linear. It can be approximated to linear with an accuracy sufficient for practice.

Methodical experiments were carried out for the determination of the initial stress state in a loess massif. Values for K_o=0.3 to 0.5 were obtained.

When the vertical stress σ_z, calculated after equation (1) and the measured horizontal stress $\sigma_{x,m}$ are known, it is possible to determine the full tensor of the stress in a given point. The slopes usually have to be treated as a two-dimension problem. The analysis of the results from the solution of the problem under two-dimensional conditions, given by Ter-Martirosyan, Ahpatelov (1982), shows that it is possible to accept, with sufficient accuracy for practical purposes, that the flow lines of the main stresses coinside with the orthogonal network in curvilinear coordinates, connecting the semi-infinite surface with straight-line limits to the semi-infinite surface with curvilinear limits, defining the slope profile. It is not difficult to find such curvilinear coordinates. In the general case it is possible to use the integral of Kristoffel-Schwars.When the angle , between the directions of the main stress and the horizontal and vertical axes is known, it is possible to evaluate the tangential stress after the equation:

$$\tau_{xz} = \frac{(\sigma_x - \sigma_z)\ tg2\alpha}{2}, \qquad (14)$$

Then the main stresses can be calculated after the equation:

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_z}{2} \pm \sqrt{(\sigma_x - \sigma_z)^2 + 4\tau_{xz}^2}. \qquad (15)$$

The full stress tensor can also be determined graphically by means of Mohr's Circle as indicated in Fig. 3.

The three-stage dynamometer method permits also the determination of the full stress tensor in any point of soil massif in the slope area by measuring the components of the stress σ_x, σ_z, σ_β (Fig. 4a).

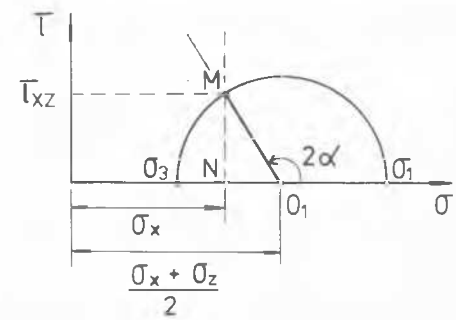

Fig. 3

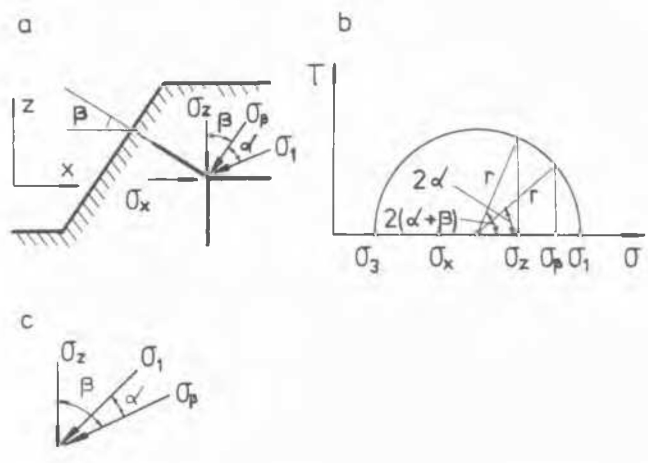

Fig. 4

From the geometry of Fig. 4b follows:

$$\sigma_z - \frac{\sigma_z + \sigma_x}{2} = r\cos(2\alpha + 2\beta) - \frac{\sigma_\beta - \frac{\sigma_x + \sigma_z}{2}}{\cos 2\alpha}\cos(2\alpha + 2\beta);$$

$$(\sigma_z - \sigma_x)\cos 2\alpha = (2\sigma_\beta - \sigma_x - \sigma_z)\cdot(\cos 2\alpha \cos 2\beta - \sin 2\alpha \sin 2\beta);$$

$$\operatorname{Cos} 2\alpha = \frac{2\sigma_\beta - \sigma_x - \sigma_z}{2r};$$

$$\operatorname{Sin} 2\alpha = \sqrt{4r^2 - (2\sigma_\beta - \sigma_x - \sigma_z)^2} \cdot \frac{1}{2r}$$

After processing and indicating:

$$\sigma_z - \sigma_x = \tau \quad \text{and} \quad 2\sigma_\beta - \sigma_z - \sigma_x = \tau_\beta,$$

we obtain:

$$r = \frac{1}{2\sin 2\alpha}\sqrt{\tau^2 - 2\tau\tau_\beta \cos 2\beta + \tau_\beta^2};$$

$$\cos 2\alpha = \frac{\tau_\beta \cdot \operatorname{Sin} 2\beta}{\sqrt{\tau^2 - 2\tau\tau_\beta \operatorname{Cos} 2\beta + \tau_\beta^2}}. \tag{16}$$

Considering that:

$$r = \frac{\sigma_1 - \sigma_3}{2} \quad \text{and} \quad \sigma_1 + \sigma_3 = \sigma_x + \sigma_z,$$

we obtain:

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_z}{2} \pm \frac{1}{2\operatorname{Sin} 2\beta}\sqrt{\tau^2 - 2\tau\tau_\beta \operatorname{Cos} 2\beta + \tau_\beta^2}. \tag{17}$$

The scheme of Fig. 4a corresponds to a case when $\tau \leq \tau_\beta \operatorname{Cos} 2\beta$, and that of Fig. 4c, when $\tau > \tau_\beta \operatorname{Cos} 2\beta$.

Except the in-situ methods, there is a laboratory way for the determination of K_o. We start from the assumption, that the stress history is reflected on the mechanical properties of the soil. Such soil properties as structural strength, anisotropy, etc. reflect the history of their loading. The structural strength is connected with the initial surface of loading, which according to the theory of plastic hardening separates the stress space into elastic and plastic deformation areas. On the basis of these assumptions, and observing the behaviour of the soil within the surface of loading, which follows the law of transversal isotopy, a method has been developed for laboratory determination of the coefficient K_o.

Two soil samples-twins are tested in the triaxial apparatus in two ways. The first sample - under compression by measuring the lateral pressure; the second sample - without possibility for axial deformation by measuring the axial pressure. Then, if these conditions are strictly observed, the relationship between the main stress σ_1 and $\sigma_2 = \sigma_3$ is linear up to certain limits (Fig. 5), the points a and b on the graph (σ_2, σ_1).

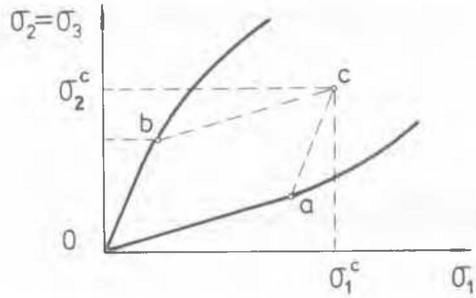

Fig. 5 Experimental relationship between the main stresses

By constructing a parallelogram on the relationship (σ_2, σ_1) with corners at the beginning of the coordinate system 0 and at the points a and b, where the linearity is violated, it is easy to determine the fourth corner c with coordinates σ_2^c and σ_1^c. Then $K_o = \sigma_2^c/\sigma_1^c$.

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