K_0-Consolidation in Triaxial Cells

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A continuous action of vertical stresses in the soil massive leads to the formation of a lateral earth pressure – horizontal stress, proportional to the vertical stress. Depending on the value of vertical stress, the lateral earth pressure can reach significant values, which requires to consider this load when designing underground structures, retaining walls, mine workings. In the simplest case the relationship between the stresses, which act in vertical and horizontal directions, is assumed to be linear and is expressed as the coefficient of lateral earth pressure K_0, similar to solid bodies:

$$K_0 = \xi = \frac{\sigma_x}{\sigma_z} .$$

For normally consolidated soils vertical stresses in the foundation exceed horizontal ones, and K_0 value is less than 1 (usually in this case it is denoted as K_0^{nc} – i.e., the coefficient of lateral earth pressure in normally consolidated soil). In this case, the analytical solutions can be obtained with the use of different suppositions.

An example can be the widely known hypothesis of A.N. Dinnik (1925), proposed on the basis of the elasticity theory solution. For the normally consolidated silty clay soils in the absence of radial displacements (under oedometric compression) was proposed the dependence on the Poisson's ratio:

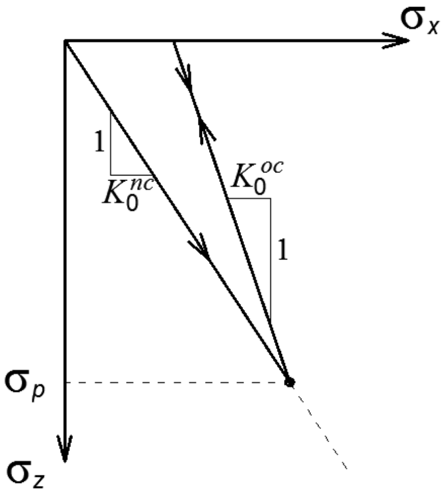
$$K_0 = \frac{\nu}{1-\nu} .$$

Another common solution for cohesionless soils was obtained by J. Jáky based on the equality of the angle of repose and the angle of friction. Having considered the problem of equilibrium of hypothetical sliding bodies in the soil body, the author obtained a formula that allows determining the coefficient of lateral earth pressure for loose and normally consolidated sands with sufficient accuracy:

$$K_0^{nc} = (1-\sin\varphi)\frac{1+\frac{2}{3}\sin\varphi}{1+\sin\varphi} \approx (1-\sin\varphi) .$$

These solutions are valid only for the primary loading of normally consolidated soils, since the solutions of the theory of an elastic solid body are applicable only in this case. Nevertheless, granular soils differ from solid bodies with the absence of rigid connection between particles, and from the point of view of analytical mechanics they belong to mechanisms, not to solid bodies: individual particles have the possibility of irreversible mutual displacement. During the primary loading, the particles are pressed into the pores, wedging neighboring particles, and horizontal pressure arises. But during unloading, the friction between the particles does not allow the horizontal stresses to dissipate completely - even when the vertical stress is completely reduced, the horizontal stress remains.

With the progress of overconsolidation, the ratio between stresses changes (horizontal stress decreases more slowly than the vertical), and as a result, the value K_0 may become equal or even greater than 1 (for overconsolidated soils the parameter is denoted K_0^{oc}). In this case, the inversion of principal stresses occurs: the major principal stress becomes horizontal, and the coefficient of lateral earth pressure ξ still does not exceed 1.



Lots of empirical formulas are used depending on the value of the consolidation ratio *OCR* and the type of soil. The most common is the formula proposed by P. Mayne and F. Kulhawy:

$$K_0^{oc} = (1 - \sin\varphi) OCR^{\sin\varphi} \approx (1 - \sin\varphi)\sqrt{OCR} .$$

Clearly, when using empirical solutions, limits of their applicability should be kept in mind. In particular, the use of parameters determined by indirect methods according to empirical dependencies is allowed when designing structures only from the first (lowest) geotechnical category, according to SP 22.13330.2016.

It may be recalled that, unlike most structural materials, the foundation is already under some stresses at the time of geotechnical calculation. Meanwhile, the strains caused by these stresses are usually neglected. In this case, the ratio between vertical and horizontal stresses is called the coefficient of lateral earth pressure at rest, that is, in the absence of strains. If, under the action of stresses, the soil is strained, i.e., there is active loading, the coefficient of lateral earth pressure may have a different value. Thus, the parameter K_0 characterizes the ratio between the orthogonal stresses (vertical and horizontal) at the foundation, and when the axes of principal stresses are rotated, it does not follow them. This makes it the most important parameter of the foundation, which is essential for the correct determination of the parameters in the mode of anisotropic consolidation, which was described earlier.

The coefficient of lateral earth pressure can be determined apart by special tests in triaxial instruments of various designs. This test mode is known, in fact, since the development of triaxial testing systems (A. Bishop, D. Henkel, 1957). In its essence, this method is very close to oedometric compression tests, but it is performed in a triaxial apparatus. In this case, the role of rigid non-deforming walls is performed by the incompressible fluid, which fills the cell. In the course of a gradual increase of the vertical pressure, the horizontal pressure of the sample on the water will also increase, producing the pressure in the fluid. As a result, the horizontal pressure increment and the coefficient of lateral earth pressure K_0 can be determined.

This method is based on determination of the coefficient of lateral earth pressure at rest as the ratio between stresses that do not cause strains. This stress state corresponds to the natural one. With the current level of development of testing equipment, this method becomes technically more complicated, since it is necessary to consider the rigidity of all elements of testing system and compensate for its deficiency in the course of experiment. Therefore, the test procedures are different for type A (conventional) and type B (K_0) cells.

K_0-consolidation in type B cells is easier to carry out due to their design features. The test is carried out with fully water-saturated samples and closed drainage, while the pore pressure is measured. The cell is connected to a piston supercharger. A pressure step of 25 kPa is applied to the top cap, which causes a radial expansion of the sample and the fluid displacement from the cell, which is compensated by a supercharger. In this case, it is possible to calculate the inherent rigidity of equipment, since pressure level is known: collateral volumetric strains in the system are compensated automatically on the basis of rating curve. After stress stabilization the operation is repeated until the vertical pressure reaches the calculated value. The ratio between horizontal and vertical stresses allows to determine the natural value of the coefficient of lateral earth pressure. This method was developed and tested in the laboratory of “Petromodeling” Company Group with participation of LLC “RPE “Geotek”.

A type B cell also makes it possible to simulate overconsolidation when using in this mode: during an increase in the vertical pressure up to the historical pressure σ_p and following unloading to the current value of natural pressure the ratio between horizontal and vertical stresses changes, which makes it possible to estimate actual horizontal stress with account of overconsolidation. This is the valuable advantage of this test mode. After performing K_0-consolidation, it is possible to continue the experiment with the same sample according to any test scheme.

In type A cells of standard design, K_0-consolidation mode is possible only with the value $K_0 \leq 1$. To perform an experiment with highly overconsolidated ($K_0 > 1$, $OCR > 3$) soils, a rigid fixation of the loading rod on the piston is required. Determination of the coefficient of lateral earth pressure is performed by a step increase in pressure in the cell. In this case, the drainage system is connected to the volume measurement system (the piston supercharger). The value of each step is 25 kPa. During the application of the confining pressure step, the resulting volumetric strain of the sample is compensated by changing the vertical pressure, so that there is no volumetric strain ε_v. After stabilization of strains the operation is repeated until the vertical pressure reaches the calculated value. In a more concise form, both methodologies are described in Annex I of the forthcoming edition of GOST 12248.3, which will allow applying it in production activities in the near future.

Triaxial compression tests in the K_0-consolidation mode is the only currently proven method for determining the coefficient of lateral earth pressure at rest. Without this parameter, it is impossible to reproduce the initial stress state, both in a laboratory sample and in a soil body by numerical simulation.

LLC “RPE “Geotek” proposes the automated testing system “ASIS pro” for axisymmetrical UU, CU, CD, K_0 triaxial tests of soil samples in the modes of anisotropic and isotropic consolidation. The system includes the cells of volumetric (type “A”) and radial (type “B”) compression for creating the triaxial stress state, and also the necessary equipment for implementation of vertical force action, cell and back pressure management. The tests are carried out in an automated mode with the control of all test parameters in real time.

More detailed technical information can be given by the company's specialists or found on the official website www.npp-geotek.ru.