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IMPROVEMENTS OF METHODS TO DETERMINE SOIL LATERAL PRESSURE EXERTED ON ENGINEERING STRUCTURES

PERFECTIONMENT DES METHODES DE LA DETERMINATION DE LA PRESSION LATERALE DU SOL SUR LES CONSTRUCTIONS INGENIEURES

P.I. Yakovlev[1] M.P. Dubrovsky[2] A.V. Shkola[1] A.N. Shtoda[3] Yu.M. Omelchenko[4] A.A. Bibichkov[5]

[1]Professor, Marine Engineering Institute, Odessa, Ukraine
[2]Associated Professor, Marine Engineering Institute, Odessa, Ukraine
[3]Assistant Manager, Black Sea Shipping Company, Ukraine
[4]Chief Engineer, Sea Port Yuzhny, Ukraine
[5]Engineer, firm "ABIK", Odessa, Ukraine

SYNOPSIS: This paper deals with improvements achieved along two lines of studies of force interaction between retaining walls of engineering structures and soil. The first part considers an ultimate (both active and passive) state of cohesive soil interacting with the wall in seismic conditions, and gives a general solution of the problem of finding the soil lateral pressure both in a traditionally assumed ("direct") direction of contact friction forces, when the soil behind the wall settles down more that the wall, and in practically occurring cases of a "reverse" direction of the above forces, when the wall sinks more than soil. The second part discusses the mixed problem of elastic/plastic anaylis and its solution to obtain the soil lateral pressure exerted on a retaining wall as a function of the nature and value of its development, which yields a "pressure-displacement" relatioship in the range from at rest to active or passive pressure.

INTRODUCTION

Methods to calculate soil lateral pressure for cases of a "reverse" direction of contact friction forces have been developed insufficiently. It is known, however, that in some instances of a "reverse" direction of friction forces active pressure can increase by two to three times. Below will be suggested most general of known formulas derived on the basis of Coulomb theory and classical theoremes of structural mechanics. Characteristic of very rigid and practically undeformable structures (massive retaining walls, walls of dry docks and locks, some berthing structures) is that due to only minor displacements an ultimately stressed state does not develop through the whole mass of soil interacting with these structures. In this connection there is a need to consider simultaneously the emergence, development and force interaction of both ultimate and subultimate soil stressed zones. The following kinematic method gives a solution to his problem avoiding bulky calculations.

GENERAL METHOD TO DETERMINE A LATERAL PRESSURE OF COHESIVE SOIL TAKING INTO ACCOUNT THE DIRECTION OF CONTACT FRICTION FORCES AND SEISMIC EFFECTS

The influence of cohesion c can be substituted with a uniform load $c/tg\varphi$ normal to backfill surface and the back face of the wall (φ - internal friction angle). Let us consider a case of active pressure at a direct action of contact friction forces (which in case of a seismic effect deflect the gravitational force by angle ω from the vertical) (Fig.1).

When constructing a polygon of forces we shall not consider the resultant of pressure acting along the back face. We shall take account of this pressure at the end of calculations when constructing the pressure diagram.

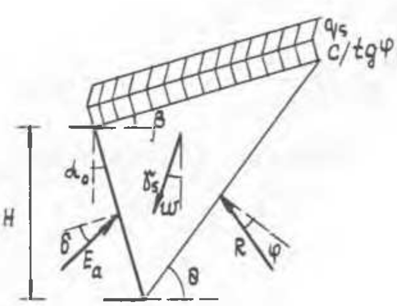

Fig.1

The value of E_a and Q depends on the angle μ (Fig.2) which can be determined from the expression

$$\mu = arctg\frac{(c/tg\varphi)\ \sin(\beta+\omega)}{(c/tg\varphi)\ \cos(\beta+\omega)+q_s\cos\beta+0.5\gamma H\cos(\beta-\alpha_0)/\cos\alpha_0} \quad (1)$$

The formula for the resultant of soil lateral pressure takes the form (Fig.2)

$$E_a = Q\sin(\theta-\varphi+\omega-\mu)/\sin(90^\circ+\alpha_0+\delta-\theta+\varphi). \quad (2)$$

The required value of angle θ is determined from the equation $dE_a/d\theta = 0$. If for simplification reasons the variable θ is substituted with variable x, plotted on the axis passing through point A at an angle $\psi = \varphi - \omega + \mu$

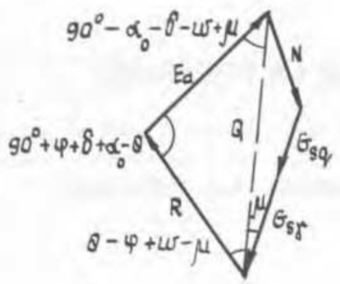

Fig.2

to the horizon (Fig.3) the position of the slip surface in plane corresponding to the maximum soil pressure shall be determined by root x_0 from equation

$$\frac{dE_a}{dx} = 0.$$

Geometrically we shall determine the weight of slip wedge $G_{s\gamma}$, the resultant force G_{sq} of surface load, the resultant N of the cohesion load and the resultant Q of the three above forces (fig.3)

$$G_{s\gamma} = 0{,}5\gamma_s H\overline{AC}/\cos(\alpha_0-\beta); \quad G_{sq} = q_s\overline{AC}\cos\beta; \quad N = c\overline{AC}/tg\varphi,$$

$$Q = \left[0{,}5(\gamma_s+2q_sK_q/H) + K_c c/(Htg\varphi)\right]H\overline{AC}/\cos\mu; \tag{3}$$

$$AC = \frac{Hx\cos(\varphi-\alpha_0-\omega+\mu)}{\cos(\alpha_0-\beta)(H+K_1x)}; \quad K_1 = \sin(\varphi-\omega+\mu-\beta)/\cos(\alpha_0-\beta);$$

$$K_q = \cos\alpha_0\cos\beta/\cos(\alpha_0-\beta); \quad K_c = \cos(\beta+\omega)\cos\alpha_0/\cos(\alpha_0-\beta)$$

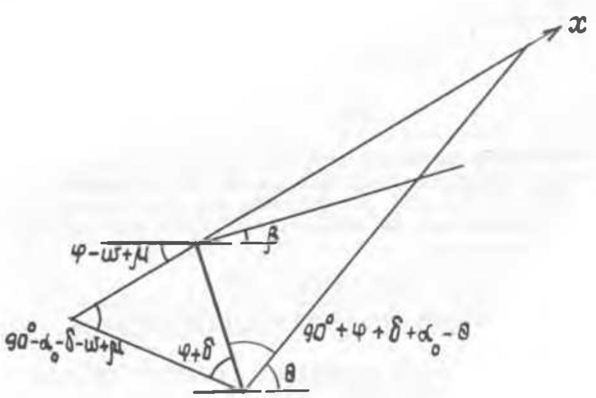

Fig.3

The trigonometrical side of equation (2) can be written in the form

$$\sin(\theta-\varphi-\mu+\omega)/\sin(90^\circ+\alpha_0+\delta-\theta+\varphi) = \left(m+\frac{nxtg\alpha_0}{H}\right)^{-1}, \tag{4}$$

where

$$m = \sin(\varphi+\delta)/\cos(\varphi-\alpha_0-\omega+\mu);$$
$$n = \cos(\alpha_0+\delta+\omega-\mu)/\cos(\varphi-\alpha_0-\omega+\mu). \tag{5}$$

Considering the equations (2)-(4) and performing the required differentiation we obtain the required root $x_0 = HK_0/\cos\alpha_0$, where $K_0 = \sqrt{m/(K_1 n)}$, and the expression for active pressure taking the form

$$E_a = \left[0{,}5\gamma_s H^2 + q_s HK_q + cHK_c/tg\varphi\right]\frac{K}{(1+\sqrt{z_0})^2}, \tag{6}$$

where

$$K = \cos^2(\varphi-\alpha_0-\omega+\mu)/\cos^2\alpha_0\cos\mu\cos(\alpha_0+\delta+\omega-\mu);$$

$$z_0 = \sin(\varphi+\delta)\sin(\varphi-\omega+\mu-\beta)/\cos(\alpha_0+\delta+\omega-\mu)\cos(\alpha_0-\beta).$$

The horizontal component of force E_a is $E_a^x = E_a\cos(\alpha_0+\delta)$, and the full horizontal component of force exerted on the wall considering the load $c/tg\varphi$ along its back face $E_{ac}^x = E_a\cos(\alpha_0+\delta) - H_c/tg\varphi$. The intensities of horizontal component of pressure related to vertical projection (Fig.4)

$$a_0 = q_s\lambda^x_{aq_s} - (c/tg\varphi)(1-\lambda^x_{ac}); \quad a = a_0 + \gamma_s H\lambda^x_{a\gamma_s}, \tag{7}$$

where

$$\lambda^x_{a\gamma_s} = K\cos(\alpha_0+\delta)/(1+\sqrt{z})^2; \quad \lambda^x_{aq_s} = \lambda_{a\gamma_s}\cdot K_q;$$

$$\lambda^x_{ac} = \lambda^x_{a\gamma_s}\cdot K_c$$

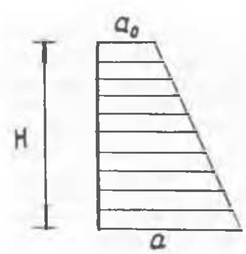

Fig.4

The angle of slip plane inclination is in this case determined by the relationship

$$tg\theta = \frac{K_0\sin(\varphi-\omega+\mu)+\cos\alpha_0}{K_0\cos(\varphi-\omega+\mu)-\sin\alpha_0}. \tag{8}$$

Now we shall consider a case of active pressure with opposite friction. This takes place when the wall's sinking is greater than soil settlement in the slip wedge. Thus, the angle δ

shall be plotted on the other side of the normal (Fig.5)

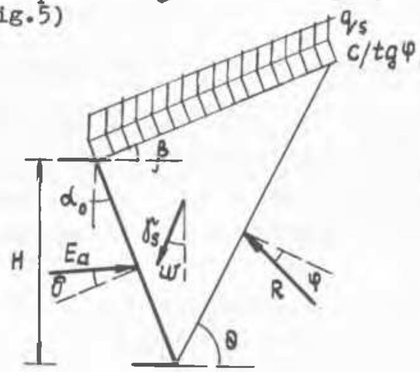

Fig.5

The formula of soil lateral pressure shall take the form (Fig.6):

$$E_a = Q\sin(\theta-\varphi+\omega-\mu)/\sin(90^\circ+\alpha_0-\delta-\theta+\varphi), \qquad (9)$$

where μ and Q shall be determined from (1) and (3).

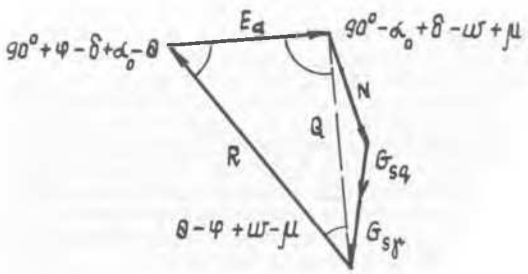

Fig.6

The trigonometrical side of equation (9) can be rewritten as

$$\frac{\sin(\theta-\varphi+\omega-\mu)}{\sin(90^\circ+\alpha_0-\delta-\theta+\varphi)} = \left(m+\frac{n\,x\,tg\alpha_0}{H}\right), \qquad (10)$$

where

$$m=\frac{\sin(\varphi-\delta)}{\cos(\varphi-\alpha_0-\omega+\mu)}; \qquad n=\frac{\cos(\alpha_0-\delta+\omega-\mu)}{\cos(\varphi-\alpha_0-\omega+\mu)}$$

Substituting (3) and (10) into (9) we shall obtain the expression for E_a in the form (6),but with the following values of parameters K and z_0:

$$K=\frac{\cos^2(\varphi-\alpha_0-\omega+\mu)}{\cos^2\alpha_0\cos\mu\cos(\alpha_0-\delta+\omega-\mu)}; \quad z_0=\frac{\sin(\varphi-\delta)\sin(\varphi-\omega+\mu-\beta)}{\cos(\alpha_0-\delta+\omega-\mu)\cos(\alpha_0-\beta)}.$$

The intensities of the horizontal component of pressure (taking into account the load $c/tg\varphi$ along the back face of the wall) related to the vertical projection shall be determined from the formulas (7) with substitution of $\cos(\alpha_0+\delta)$ for $\cos(\alpha_0-\delta)$.
Performing the same manipulations we shall obtain a formula to determine the slip angle which will have the form similar to formula (8). K_0, however, shall be determined from the following expression:

$$K_0=\sqrt{m/(K_1 n)}=\sqrt{\frac{\sin(\varphi-\delta)\cos(\alpha_0-\beta)}{\cos(\alpha_0-\delta+\omega-\mu)\sin(\varphi-\omega+\mu-\beta)}}.$$

Also, calculation formulas have been derived and similar constructions carried out for the case of passive pressure emerging both in the "direct" and in the "reverse" direction of contact friction forces.
The above studies allow us to do the following generalised conclusions:
- the expressions (1), (6), (7) and (8) for active pressure at direct friction can be used in all calculations with respective correction of angle signs;
- to calculate active pressure with a reverse friction, a negative (with a minus sign) angle δ should be substituted in the above formulas;
- to calculate passive pressure at direct friction conditions negative angles φ, δ, ω, are substituted to the above formulas, and in the formulas (7) a plus sign before the radical is substituted with a minus sign;
- to calculate passive pressure at reverse friction conditions negative angles φ, ω are substituted in the above formulas, and in the formulas (7) a plus sign before the radical is substituted with a minus sign.

In a particular case of non-cohesive soil $C=N=\mu=0$ should be assumed.

KINEMATIC METHOD OF DETERMINING LATERAL SOIL PRESSURE IN MIXED PROBLEM OF ELASTIC/PLASTIC ANALYSIS

To consider the problem the following preconditions have been assumed (Fig.7):

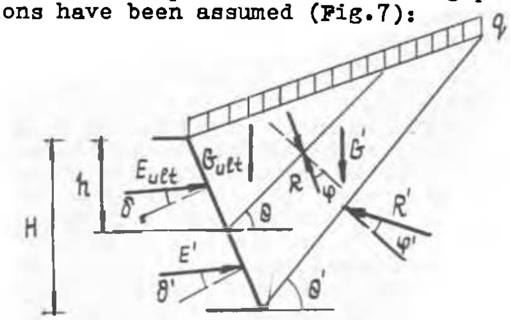

Fig.7

a) the nature of stressed state at an arbitrary point of the structure's lateral surface contacting with soil is determined by the horizontal displacement u (z) ratio of the structure's cross)section to depth z of this cross-section from the surface of soil. Then at $u(z)/z<\alpha$ the soil will be in a subultimate state, and in the opposite case in the ultimate stressed state. Proceeding from known experimental studies it can be assumed that when active pressure is developed $\alpha=\alpha_a=0.001\div0.0015$, and when passive pressure is developed $\alpha=\alpha_p=0.01\div0.03$. This precondition differs from a commonly accepted condition of an ultimate state development, which is characterized by a ratio of critical displacement of the wall to its height $u_{cr}/H\alpha_0$. This requires some explanations. Obviously, the process of soil transition within the interval of displacements $[0-u_{cr}]$ from the at rest state to the ultimate stressed state is smooth, and not abrupt.Thus, in the course of displacement the part of soil contacting the wall (probably in the topmost contacting with the surface part of the wall) is in an ultimate stressed state, and a part of soil contacting with the wall surface (closer to its bottom) is in a subultimate stressed state. Hence, the ratio u/H when it becomes equal α (at $u = u_{cz}$) characterized not a current, but only a final stressed state (which corresponds to the transition of the whole soil contacting with the structure to an ultimate state), which may not set in at small displacements of some structures;

b) the boundary of ultimate and subultimate stressed zones (or the height h of ultimately stressed soil contacting the structure) can be found from the conditions $u(h)/h=\alpha$, to use which we must specify the form of the function $u(z)$, determined by the nature of the structure's deformations (e.g for a rigid structure the function will be linear);

c) the deviation angles of the soil lateral pressure resultant from the normal to the contacting face of the structure, and the resultant of reactive pressure of the soil mass behind the thrust (or reactive) wedge from the normal to the boundary of this wedge are assumed for the zone of ultimate stressed state δ and φ respectively (with $\delta = m\varphi$, where $0 \le m \le 1$), and for the zone of subultimate stressed state δ' and φ' respectively, with $\delta' = \delta_0 + n(\delta - \delta_0)$; $\varphi' = \varphi_0 + n(\varphi - \varphi_0)$, where parameter n is a function of relationship between the sizes of the zones of ultimate and subultimate stressed states of soil ($0 \le n \le 1$) determined by the ratio V_{ult}/V. Here V_{ult} and V are the volume of soil wedge in an ultimate stressed state, and of the whole soil interacting with the structure's contact face respectively, determined form geometrical considerations in conformity with the assumed form of slip surfaces; $\delta_0 = m\varphi_0$, φ_0 is an arbitrary soil internal friction angle at the rest pressure;

d) both stressed state zones in the mass of soil interacting with the structure are limited either by flat or curvilinear slip surfaces constructed by traditional methods using angles φ and δ for the ultimate zone with depth , and angles φ' and δ' for the subultimate zone $H-h$ (H=height of retaining wall). The calculation relationships to find the thrust and reactive soil pressure are found from general formulas which in the above cases differ only by signs of angles φ, δ or φ', δ';

e) the resultant E of lateral (thrust and reactive) soil pressure exerted on the structure is determined as an algebraic sum of the ultimate E_{ult} (acting in the area with height h) and the subultimate E', acting in the area with height $H-h$, components taking into account respective angles δ and δ' :

$$\vec{E} = \vec{E}_{ult} + \vec{E}' = \left[E_{ult}^2 + E'^2 + 2E_{ult}E'\cos(\delta - \delta') \right]^{1/2}.$$

To find the above components of lateral pressure one should consider successively the equilibrium conditions for the ultimate and subultimate soil wedges, the geometry of which is determined by the assumed form of the slip surface. This aproach made it possible to obtain calculation relationships to find the components: E_{ult} which increases form zero (no displacements) to active or passive pressure (depending on the direction of displacement of the structure's contacting face), and E', respectively decreasing from the at rest pressure to zero, as a function of u (z) for flat and curvilinear slip surface, which have been realized in a computation program for IBM PC. The calculation of "structure-soil" system where solving an elastic/plastic problem makes it possible to obtain in the range of pressures from active to passive a calculation relationship for the resultant of soil lateral pressure $E = E(u)$ (Fig.8).

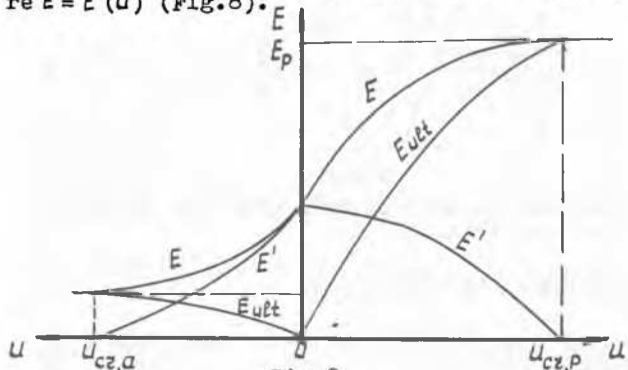

Fig.8

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