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Assessment of soil lateral pressure depending on retaining wall displacements

Définition de la pression latérale du sol suivant le déplacement de mur de soutènement

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ABSTRACT
Early (on XIII and XIV International Conferences on Soil Mechanics and Foundation Engineering in Delhi, 1994 and in Hamburg, 1997, as well as on XI, XII and XIII European Conferences on Soil Mechanics and Geotechnical Engineering in Copenhagen, 1995, Amsterdam, 1999 and Prague, 2003) were motivated, considered and discussed main aspects of new interaction model of the system «retaining wall - soil media». This model allows to take into account kinematics factors of the considered system and to use when designing and calculating variable values of main system parameters, corresponding to its current deformed and stressed states. Main results of the model further development and its applied aspects are presented in the paper. In wide range of displacements provided active and passive soil pressure dependencies "displacement – pressure" are studied including peculiarities related to the state at rest.

RÉSUMÉ
Les aspects principaux de nouveau modèle d'interaction des éléments du système "mur de soutènement - sol" avaient été argumentés, examinés et considérés avant (lors des XIII et XIV Conférences internationales sur la mécanique des sols et la construction des fondations à Delhi, en 1994 et à Gambourg, en 1997, ainsi que lors des XI, XII et XIII Conférences européenes sur la mécanique des sols et la géotechnique à Copenhague, en 1995, en Amsterdam, en 1999, à Prague, en 2003 - voir les réferences). Ce modèle permet de prendre en considération les caractéristique cinématiques du système examiné, ainsi qu'utiliser les valeurs variables des paramètres essentiels du système correspondants à son état courant tendu et déformé lors d'établissement de projet et des calculs. Les resultats essentiels du développement ultérieur de ce modèle et de ses aspects appliqués sont présentés dans l'exposé. Les dépendances "déplacement - pression" sont étudiées en vaste diapason des déplacements assurant la pression dans l'étendue d'active au passive, y compris la considération des particularités de la pression en état de repos.

1 INTRODUCTION

Practically in many cases structures included rigid retaining walls (dry docks, locks, quay walls and others) are erected on deformed soils. When the external load is exerted upon the structure its foundation slab may settle and rotate following the deformations of the ground below. This causes rotating of the retaining wall as well as changes in soil lateral pressure values and distribution.

To describe a behavior of the considered structures more exactly it is necessary to define a lateral pressure of soil in accordance with its realized deformed state in the interval from the pressure at rest to pressure corresponded to the current value of generalized displacement (in the limit - to active or passive pressure depending on directions of retaining wall moving).

Soil pressure at rest, alongside with active and passive pressure, is one of the basic characteristics used at the analysis of stressed - deformed state of the system «retaining wall – soil media». The role of this parameter is especially significant when considering rigid constructions, which displacements or deformations are insufficient for realization of an active or passive pressure.

Eurocode 7 supposes use of certain "intermediate" values of soil lateral pressure when displacements of a retaining wall are insufficient for mobilization of ultimate values. Ukrainian and Russian codes recommend calculating soil pressure at rest as active pressure using some conditional angle of internal friction of the soil.

2 DEVELOPMENT OF THE KINEMATICS APPROACH

In the applying kinematics approach (Doubrovsky 1995, Doubrovsky et al 1997, Yakovlev et al 1994), when determining a soil lateral pressure, the essential role plays a parameter α stipulated the value of contact height *h* of the structure with the soil in ultimate stress state (or position of the border between zones of soil in ultimate and subultimate stress states. Value of this parameter possible to fix coming from available experimental data. Thus, in particular, on the base of known experiments (researches of V. Yaropolsky, G. Klein, P. Prokofiev, D. Taylor, K. Terzaghi, P. Yakovlev and others) it is possible to access that when forming an active pressure α_a = 0.001- 0.0015, and when arising a passive pressure α_p = 0.01-0.03.

However the possibility of getting inaccuracy stipulated by the unlikeness of conditions of interaction of the soil with structure in situ and with experimental models, as well as rather broad interval of determination of parameter α (particularly in case of passive pressure development), indicate the practicability of determination of values of α by accounting (theoretical) way.

As far as any displacement of the structure (to the soil or from it) causes changes in soil density and porosity it is possible to connect parameter α with soil void ratio. Let soil pressure at rest E_o corresponds to certain value of void ratio e_o, active pressure E_a - to value of void ratio e_a, passive E_p - to value of void ratio e_p (the last can be determined as a void ratio for soil in state of maximum density). To shorten the record we will use that the ultimate pressure E_e (E_a or E_p) corresponds to the value of void ratio e_e (e_a or e_p). Specified values of the void ratio are to be determined on the base of laboratory tests.

Changes in porosity of soil in sliding and bulging wedges is stipulated by the increments of their volume during corresponding displacements of the structure. To obtain the relationship between structure displacement and void ratio let equate an increment of volume of the wedge with corresponding increment of pores' volume.

In the case of onward displacement combined with the rotation respectively the lower end of the structure for the arbitrary point on contact surface of retaining wall the sought parameter is defined as (Doubrovsky 1994): $\alpha = U(Z)/Z$.

In the process of wall moving a soil void ration changes from value $e_O = V_P/V_T$ (V_P = a pores' volume of the soil interacting with structure at rest; V_T = volume of soil skeleton) to value $e_{Oe} = (V_P + \Delta V_{Pe})/V_T$

(ΔV_{Pe} = an increment of pores volume, corresponding to the critical displacement U_e (Z) at realization of active or passive pressure).

As obtained for such approach (Doubrovsky 1999)

$$\alpha_P = 2P\cdot (e_O - e_e)/(1+e_O) - U_B/z, \qquad (1)$$

where

$$P = \frac{(\mathrm{tg}\,\alpha_O + \mathrm{tg}\,r)\cdot(1+\mathrm{tg}\alpha_O\cdot \mathrm{tg}\beta)}{2(1-\mathrm{tg}\,\beta\cdot \mathrm{tg}\,r)},$$

α_O and β = accordingly angles of the wall contact surface with vertical and of soil backfill surface with horizon.

Under onward wall displacement without the rotation, when $r_O = 0$ and $U_в/Z = \alpha_P$ from the dependency (1) we can get

$$\alpha_{PU} = P\cdot (e_O - e_e)/(1+e_e) = \mathrm{const}, \qquad (2)$$

i.e. sought parameter does not depend on the height (or on the coordinate z) and is defined only by physical parameters of soil and by geometry of the system " structure - soil media".

At wall rotation respectively its lower end without onward displacement , when U= 0, we have

$$\alpha_{Pr_o} = 2P\cdot(e_O - e_e)/(1+e_e) - H\,[\mathrm{tg}\,\alpha_O - \mathrm{tg}\,(\alpha_O - r_o)]/z,$$

i.e. in this case sought parameter changes on the height of the wall and is defined not only by factors, characterizing dependency (2) but also by kinematics parameter such as angle of rotation r_o.

In the event of curvilinear sliding surfaces on the grounds of earlier obtained dependencies (Doubrovsky 1994, 1997, Doubrovsky et al 1995) it is possible to write:

$$\alpha_K = 2K\cdot (e_O - e_e)/(1+e_e) - U_B/Z. \qquad (3)$$

where

$K = 0{,}5\cos\eta_e\,\{[\cos\eta_e\cos(\theta_{1e} - \beta)\exp(\pm 2\theta_e\,\mathrm{tg}\,\varphi_e)]/\sin(\theta_{1e} - \beta \pm \varphi_e) + \sin\varepsilon_e + 0{,}5\cos\eta_e[\exp(\pm\theta_e\,\mathrm{tg}\,\varphi_e) - 1]/\sin\varphi_e\}/[\cos^2\alpha_O\cos\varphi_e]$;

$\varepsilon_e = 0{,}5\,\{0{,}5\pi \pm (\delta_e - \varphi_e) - \arcsin[(\sin\delta_e)/(\sin\varphi_e)]\}$; $\eta_e = \varepsilon_e \pm \varphi_e$;
$\theta_e = \theta_{1e} - \varepsilon_e - \alpha_O$; $\theta_{1e} = -0{,}5\{\pm\varphi_e - \arccos[\sin\beta/(\pm\sin\varphi_e)] - \beta\}$

(note: plus corresponds to the active and minus - to the passive pressures).

Under onward wall displacement without the rotation, when $r_o = 0$ and $U_B/Z = \alpha$ from the dependency (3) one can get $\alpha_{KU} = K\cdot (e_O - e_e)/(1+e_e) = \mathrm{const}$, and at wall rotation respectively its lower end without onward displacement (U= 0):

$$\alpha_{Kr_O} = 2K\cdot (e_O - e_e)/(1+e_e) - H\,[\mathrm{tg}\,\alpha_O - r_O)]/z.$$

Thereby, qualitative features of parameter α under curvilinear sliding surfaces are similar to obtained under flat sliding surfaces above.

In the case of onward displacement combined with the rotation respectively the upper end of the wall:

$\alpha = 2V(Z)\cdot(e_O - e_{Oe})/[(1+e_e)\cdot z^2] - U/Z$,

i.e. for the considered type of the wall displacement the sought parameter does not depend on the rotation angle r_o and is defined only by physical parameters of soil and by geometric parameters of system "structure - soil media".

Under rotation respectively the upper end of the wall without onward displacement (when U=0):

$\alpha_{Pr_O} = 2P\cdot(e_O - e_e)/(1+e_e)$ and

$\alpha_{Kr_O} = 2K\cdot(e_O - e_e)/(1+e_e)$.

In general cases of considered complex displacements ($r_O \neq 0$; $U \neq 0$):

$\alpha_P = 2P\cdot(e_O - e_e)/(1-e_e) - U/Z$ and

$\alpha_K = 2K\cdot(e_O - e_e)/(1-e_e) - U/Z$.

Thereby, are received calculation dependencies allowing to define a border of ultimate and subultimate stress state of the soil under general and particular cases of structure displacements to the soil ($e_e = e_p$) or from the soil ($e_e = e_a$) for methods, based on hypothesizes as flat and curvilinear sliding surfaces.

As an example let's consider the retaining wall, which height of vertical contact surface is H = 15 м, interacting with sandy back filling, having horizontal surface and characteristics: $\varphi = 24^0$; $e_O = 0.479$; $e_a = 0.485$, $e_p = \ =0.429$ (Doubrovsky et al 1997), it is obtained for the depth z = H under the assumption of flat sliding surface $\alpha_a = 0.00193$ and $\alpha_p = 0.0163$. Obtained values of parameters α_e fall into experimentally obtained intervals of the relation U_e / H and allow to refine values of these parameters for real conditions of operated structure.

3 PRESSURE AT REST

In earlier published work (Doubrovsky, 2001) the concept of so-called «threshold of gravitation» was presented. It is caused by an inequality of values of soil pressure at rest, corresponding to potential displacement of a retaining wall away from a soil (preliminary stage of active pressure) and towards a soil (preliminary stage of reactive pressure).

The physical sense of this parameter may be explained as follows. The soil active wedge is formed almost simultaneously with the beginning of wall's displacement as result of action of friction forces promoted by a gravity of a soil. At wall's displacement towards a soil its (soil) gravity interferes with displacement. So only as a result of overcoming this factor (which is offered to assess numerically by value of "threshold of gravitation») action of friction forces in a soil results to formation of a reactive prism (figure 1).

As pressure at rest is the important starting point at definition of stressed - deformed state of the system «retaining wall – soil media» in many geo-engineering important designs (deep-water quay walls, walls of dry docks, tunnels, etc.), perfection of methods of definition of this base parameter essentially influences both reliability of a construction, and on its technical and economic parameters.

On the basis of the known experimental researches (for example, Lubenov, 1962, Yakovlev, 1968, 1987), it is possible to assume (similarly to formation of sliding surfaces corresponding to active or reactive wedges at the wall's displacement), that some conditional soil wedge corresponds to the soil pressure upon the motionless wall (wedge at rest). As discovered, the sizes of this wedge exceed dimensions of an active wedge.

a

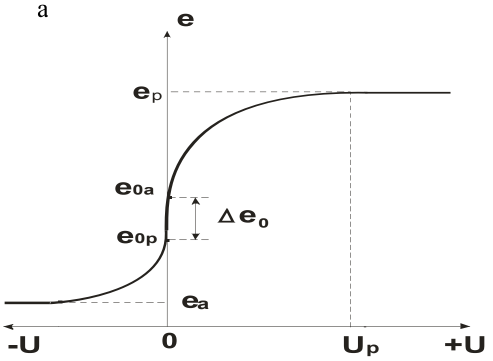


Figure 1. Illustration to proposed approach: dependences of soil lateral pressure on a retaining wall's displacements

It is logical to assume, that in case of an opposite direction of construction displacement (towards a soil) dimensions of the wedge at rest will increase, aspiring in a limit to the sizes of the wedge corresponding to passive pressure. At an initial stage of this process (at the exerting of external loading, but prior to the beginning of wall displacement towards a soil) there is a rearrangement of a stressed state of the soil interacting with a retaining wall. Thus the conditional active wedge (stipulated by active soil pressure behind the wall) is transformed to a conditional reactive wedge because an external lateral loading on a wall compensates initial active soil pressure. When external lateral loading on a wall reaches the value capable to cause displacement of a construction towards a soil, the conditional reactive wedge is transformed to real one. At the moment when reactive pressure reaches value of passive pressure (at the ultimate state) this reactive wedge can be transferred to the soil bulging wedge. Considered process is characterized not only by increasing of the sizes of the reactive wedge, but also by change of its geometry because the conditional angle of internal friction (on which geometrical parameters of reactive edge depend) increases (in a limit) up to value of an angle of internal friction.

Let's name the pressure corresponding to the initial stage of formation of soil stressed state regarding potential wall displacement towards the soil (for example, during the initial moment of the exerting on the retaining wall of external lateral loading) as pre-reactive pressure. Similarly, the pressure corresponding to the initial stage of formation of soil stressed state regarding potential wall displacement away from the soil will be named as pre-active pressure.

Hence (regarding above mentioned circumstances), pre-reactive pressure will be more than pre-active one. As pre-reactive pressure (considering its formation and realization) is similar to reactive one (in ultimate state – to passive pressure) it is expedient to apply formulas related to calculation of reactive pressure, but using values of an angle of internal friction of the soil, corresponding to its current stressed – deformed state. Thus, the soil stressed state on contact to a motionless retaining wall in researched model is described not by a point e_o on an axis of pressure (as in the traditional approach), but by a piece limited from below to value e_{oa} (the pressure at rest determined on dependences for active pressure), and from above – value e_{op} (the pressure at rest determined on dependences for reactive pressure). Thus, the entered concept of "a threshold of gravitation» can be described by the expression $\Delta e_o = e_{op} - e_{oa}$, where e_{op} and e_{oa} – soil lateral pressure at rest, determined accordingly under formulas for reactive and active pressures.

For quantitative assessment of the considered process the relative parameter can serve (we'll name it as factor of the transformation). Factor of the transformation is equal to the ratio of considered values of soil lateral pressure at rest: $K_t = e_{op} / e_{oa}$.

To calculate values of pressure at rest it is necessary to use corresponding values of soil internal friction angle φ_o. In work of Klein, 1977 the following dependence was offered: $\varphi_o = arcsin\,(1\text{-}K_o/1\text{+}K_o)$, where K_o – factor of soil lateral pressure at rest.

It would be methodological correctly to link a conditional angle of soil internal friction with its real values. With this purpose Jaki formula can be applied for granulated soils: $K_o = 1\text{-}sin\,\varphi$, whence in view of the previous dependence, the formula connecting conditional and real angles of soil internal friction can be obtained, as: $\varphi_o = arcsin\,[sin\varphi/(2\text{-}sin\varphi)]$.

Below some results of the qualitative and quantitative analysis of the data received by numerical modeling of interaction of elements of system «a retaining wall - the soil media» are considered. On the basis of the developed model influence of its base initial data (an angle of internal friction φ and an angle of friction δ of the soil on a contact surface of a wall) on parameters of soil lateral pressure at rest have been studied. For simplification of the analysis the retaining wall of gravitational type with a vertical rear contact side and a horizontal unloaded free surface of filling behind of a wall was considered regarding the following intervals of angles φ and δ:

- $\varphi = 22^0, 24^0, 26^0, 28^0, 30^0, 32^0$;
- δ = 0; 0,25φ; 0,5φ; 0,75φ; φ.

Resulting lateral pressure of a soil upon a construction can be received from known expression $E = 0{,}5\ \gamma\ h^2 K$, where γ – unit weight of a soil; h - height of a vertical contact side of a retaining wall; K - factor of lateral pressure of a soil. It is convenient to present the soil lateral pressure caused by its weight in the dimensionless form: $e = E/(0{,}5\ \gamma\ h^2)$, where e - the dimensionless force of lateral pressure of the ground, numerically equal to factor of corresponding lateral pressure (active, passive, or at rest).

The numerical analysis was executed for both flat and for curvilinear surfaces of soil sliding. Formulas for calculation of soil lateral pressure for considered wall can be obtained from known more general dependences (Doubrovsky and Yakovlev, 2001 and other works). Some basic qualitative and quantitative results of the numerical analysis of soil lateral pressure at rest on a retaining wall are presented in Table 1.

Table 1. Some results of numerical modelling

	flat surfaces of sliding		curvilinear surfaces of sliding	
	influence of an angle of internal friction φ (values interval 22^0-32^0)			
	no contact friction (δ = 0)	full contact friction (δ = φ)	no contact friction (δ = 0)	full contact friction (δ =φ)
Increase of factor of soil lateral pressure	1,10 - 1,61	1,81 – 3,30	1,10 - 1,61	1,71 - 2,91
Increase of factor of transformation	2,80 - 4,36	4,45 – 8,93	2,80 - 4,36	4,10 - 7,66
	influence of an angle of contact friction δ (values interval 0 – φ)			
	φ=24^0- 32^0		φ=24^0- 32^0	
Increase of a threshold Δe	1,68 - 2,05		1,59 - 1,81	
Increase of factor of transformation	1,59 – 2,047		1,46 - 1,76	

Regarding influence of an angle of internal friction φ and angle of contact friction δ, the basic qualitative conclusion on character of this influence is that with increasing of value of φ and δ the value of "a threshold of gravitation» and, accordingly, factor of transformation, also increase.

On figures 2 and 3 some samples of calculated dependencies are presented.

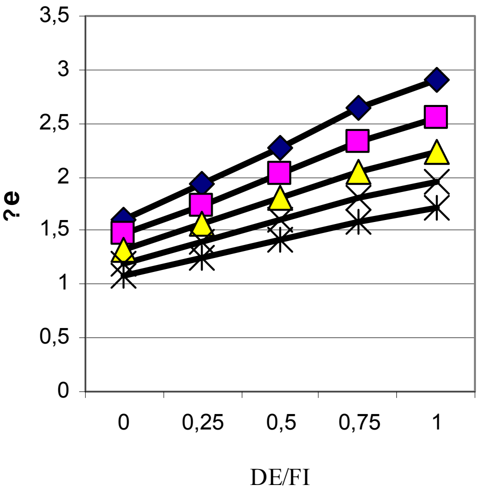
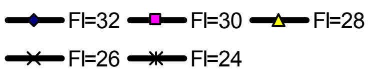


Figure. 2. Dependence between "threshold of gravitation" and angle of soil contact friction (curvilinear surfaces of sliding)



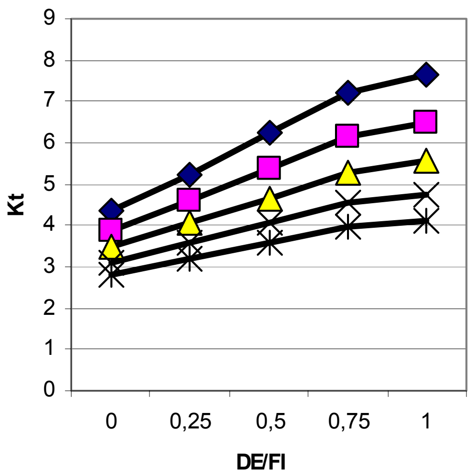
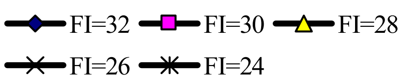


Figure 3. Dependence between factor of transformation and angle of soil contact friction (curvilinear surfaces of sliding)



4 CONCLUSIONS

Obtained solutions give possibility to consider structure/soil interaction more refinery due to possibility of determination of border between zones of ultimate and sub-ultimate stressed state of the soil interacting with retaining wall. Also one can take into account different kinds of the structure’s displacements.

Consideration of such concepts as "pre-active" and "pre-reactive" lateral pressures at rest allows taking into account a potential direction of displacement and deformations of a construction. For an estimation of quantitative distinction between "pre-active" and "pre-reactive" soil lateral pressure at rest such parameters as «a threshold of gravitation» and factor of transformation are proposed and practically implemented in numerical analysis of retaining walls. As "pre-active" soil lateral pressure at rest can exceed "pre-reactive" pressure in times (in an interval from three up to eight times depending on a soil properties), the account of the proposed parameters can increase essentially accuracy of designing and calculation of retaining walls and so to affect reliability and technical and economic parameters of constructions. It is determined that increasing of both angles φ and δ is accompanied by increase both «threshold of gravitation» and factor of transformation.

As is known, values of active pressure, calculated both for flat and curvilinear surfaces of sliding differ insignificantly, but values of reactive (passive) pressure occur to be more exact (i.e. corresponding to the data of tests) in case of use of curvilinear surfaces of sliding. In this connection it may be recommended also to apply the formulas corresponding to curvilinear surfaces of sliding while determining soil pressure at rest and related parameters: «a threshold of gravitation» and factor of transformation.

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