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Calculation theory of trench stability nearby subway tunnels while constructing by 'slurry trench' method

Théorie du calcul de stabilité des tranchées pour les parois moulées dans le sol à proximité de tunnels de métro

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ABSTRACT: The methods and algorithm of calculation of the ensured minimum of stability coefficient of deep trench walls have been developed.These methods are based on the realization of arch effect in soil with it possible collapse inside trench. Depth and length of trench , weight of soil masses in the region of possible collapse , it cohesion and angle of internal friction , level of underground waters , value of acceleration of soil vibrations from the action of subway or another sources of vibrations , unit weight and level of bentonite mortar in trench were taken as initial data.

RESUME: La methode et l'algorithme du calcul de coefficient de stabilite minimum pour les parois des tranchees profonde sont elabores.Le calcul est base sure la realisation de poussee de voute et possible rupture de talus dans la tranchee.Les donnees pour le calcul sont: la profondeur et la longueur de tranchee, le poids de sol , la cohesion et l'angle de frottement de sol , le niveau de la nappe aquifere , la valeur de acceleration de sol oscillation sous l'influence de metro , le poids specifique et la niveau de suspension de bentonite dans la tranchee .

The problem of stability of the trench , filled with bentonite mortar , as static problem was considered in the papers by J.Nasch,G.Jones 1963; J.Costet, G.Sanglerat 1981 ; G.Schneebeli 1964 ; A.Piaskowski, Z.Kowalewski 1964 , where the essentials of theoretical considerations of trench stability were laied . Significant function of arch effect in soil and level of ground waters were clarified there. However , cohesion of soil was not taken into account and the simplified diagram of distribution of stresses in depth was taken.
Herewith you'll find the calculation method , accounting not only static, but dynamic stresses as well in soil from the action of transport and industrial sources of vibrations or from seismics action.
Let's take the form of the body of soil collapse in trench [Piaskowski and Kowalewski 1965,1961] as parabolic vertical cylinder. Horizontal section of it is the segment with the base , coinciding with the wall of trench [Fig.1]. This cylinder is limited by the inclined plane at the bottom , making the angle α with the gorizont and rising from the bottom of trench at the depth h .

Such form of collapse is close to the actual one and is characterised by four parameters. Two of them l and h are given , the third one – d , characterising the formation of arch effect in soil with the angle of internal friction φ, is defined from the expression

$$d = l/2\mathrm{tg}\varphi \qquad [1]$$

that follows from the condition of limit equilibrium of parabolic arch [Nasch, Jones 1981 ; Piaskowski, Kowa–lewski 1965, 1961] , and the fourth parameter α should be defined from the condition of maximum of the resultant F of soil active pressure.

The diagram of the forces , acting on the body of collapse in the limited state , is given in Fig.2.
Let's make the system of equations of instantaneous equilibrium :

$$Q_1 + Q_2 - N\cos\alpha - T\sin\alpha = 0$$
$$k(Q_1 + Q_2) + N\sin\alpha - T\cos\alpha - F = 0 \qquad [2]$$

where :
- Q_1 – weight of part of soil above the level of ground waters;
- Q_2 – weight of part of soil lower than the level of ground waters, defined from taking into account the weighted action of water;
- N&T – normal and tangent components of the resultant of soil shear resistance along the inclined surface;
- $k = a_a/g$ – coefficient of dynamics , being the relation–ship of amplitude of soil vibrations a_a and acceleration of gravity G ;
- F – the resultant of the force of soil active pressure on ben–tonite mortar in trench , being defined without accounting hydrostatic pressure of ground waters.

Acceleration of soil vibrations can have any direction , but the least favourable direction for trench to be stable does not differ much from the horizontal one , therefore dynamic forces of inertia of soil were taken to be directed horizontally to trench in the system of equations [2] .
The diagram of loss of stablity of trench wall includes complete separation of vertical parabolic surface of body of collapse from the rest ground, therefore the action of any forces is not taken into account here , but the force of friction , expressed by Coulomb , finishes the system of equations [2] :

$$T = cS + N\mathrm{tg}\varphi \qquad [3]$$

where c and φ – unit cohesion and angle of internal friction of soil.
This force of friction acts upwards along the inclined plane of S square.

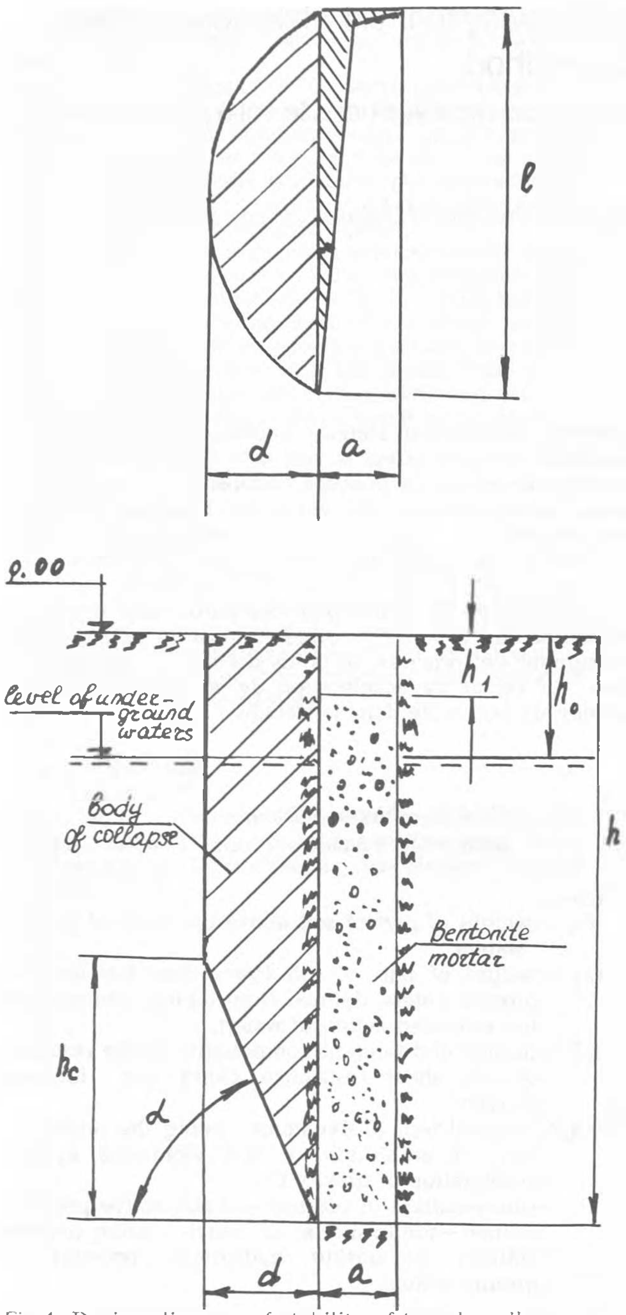

Fig.1. Design diagram of stability of trench wall.

The combined solution of the equations [2] and [3] ,regarding some geometric transformations , leads to the following result :

$$F = k(Q_1+Q_2) - \frac{cl^2}{3tg\varphi} + tg(\alpha-\varphi)\; Q_1 + Q_2 - \frac{cl^2 tg\alpha}{3tg\varphi} \qquad [4]$$

Weight of soil is defined in the parts , having the volumes V_1 , V_2 and V_3 :

$$Q_1 = \gamma V_1 ; \quad Q_2 = \gamma'(V_2 + V_3) \qquad [5]$$

where γ and γ' — unit weight of the soil , disposed above and below the level of ground waters;

$$V_1 = \frac{2}{3} dlh_0\gamma ; \quad V_2 = \frac{2}{3} dl(h-h_0-dltg\alpha); \quad V_3 = \frac{2}{5} d^2ltg\alpha$$

Having made geometric transformations , accounting

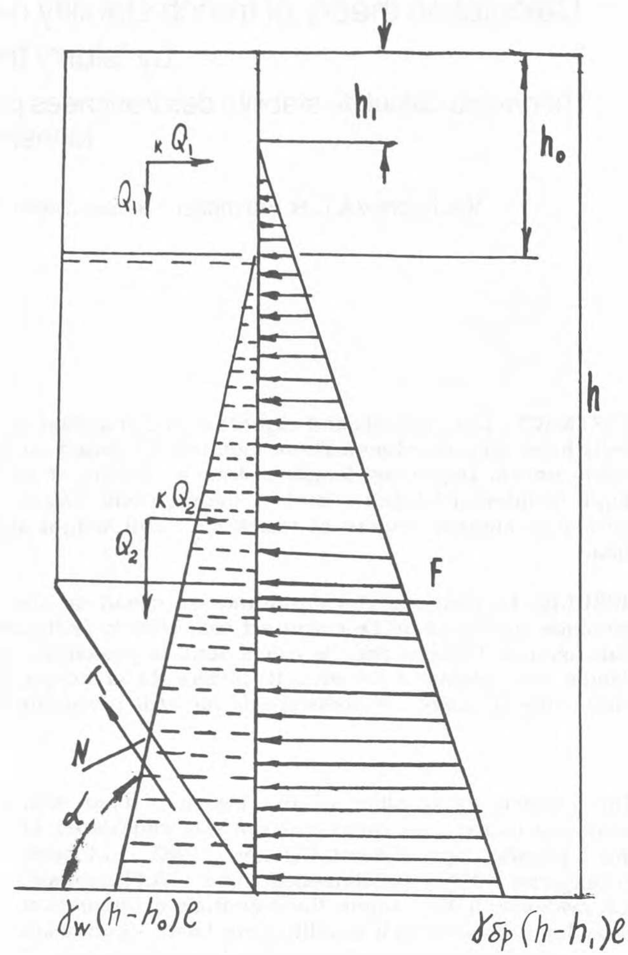

Fig.2. Diagram of the forces, acting on the body of collapse in the limit state

relation [1] from the expression [4] , we have the formula of the resultant of active pressure of soil onbentonite mortar in trench :

$$F = l^3 \frac{tg(\alpha-\varphi)+k}{3tg\varphi} \frac{h_0}{l} \gamma + \frac{h-h_0}{l} \frac{tg\alpha}{5tg\gamma} \gamma' - \frac{cl^2}{3tg\varphi} \; 1 + tg\alpha tg(\alpha-\varphi) \qquad [6]$$

The condition $dF/d\alpha = 0$ may be used to define maximum of the function $F[\alpha]$, however this condition leads to transcendental equation. Maximum of active pressure can be defined from numerical method of successive approximations by the extremum of function $F[\alpha]$ with the variations of parameter α .
The coefficient of total stability of trench K_{st} at the depth being considered can be defined from the least favourable relation of the moments of holding and dumping forces :

$$K_{st} = F_{bm}/(2F + F_2) \qquad [7]$$

where
F_{bm} — resultant of pressure of bentonite mortar ;
F_2 — resultant of hydrostatic pressure of water ;

The force F_{bm} is spaced from the low point on one third of the depth , but the force F can not be spaced higher than two thieds of this depth , therefore relation

Table 1

Initial data	Results of calculation			
	h_1(m)	k_a	F(kN)	α
l=3.0; h=28.0m; h_0=0	0	1.17	142.3	65^0
c=59.0kPa; k=0.06	1	1.09	142.3	65^0
$\gamma = 18kN/m^3$; $\varphi = 39^0$	2	1.01	142.3	65^0
$\varphi' = 11kN/m^3$; $\gamma_{bm} = 12kN/m^3$	3	0.93	142.3	65^0

Table 2

Initial data	Results of calculation			
	h_1(m)	k_a	F(kN)	α
l=3.0; h=37.6m; h_0=0	0	1.22	137.9	57^0
c=134.0kPa; k=0.06	1	1.15	137.9	57^0
$\gamma = 18kN/m^3$; $\varphi = 35^0$	2	1.09	137.9	57^0
$\varphi' = 11kN/m^3$; $\gamma_{bm} = 12kN/m^3$	3	1.03	137.9	57^0

Table 3

Initial data	Results of calculation			
	h_1(m)	k_a	F(kN)	α
l=2.8; h=14.0m; h_0=6.0m	0	1.16	823.6	58^0
c=30.0kPa; k=0.06	1	1.00	823.6	58^0
$\gamma = 17.4kN/m^3$; $\varphi = 12^0$	2	0.85	823.6	58^0
$\varphi' = 7.8kN/m^3$; $\gamma_{bm} = 10.7kN/m^3$	3	0.71	823.6	58^0

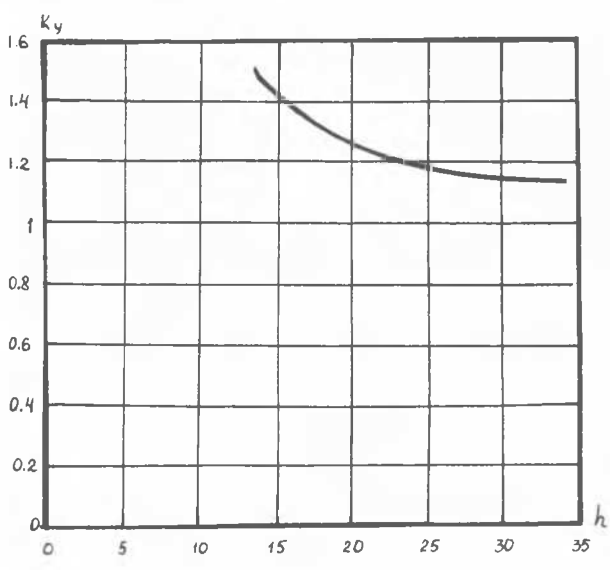

Fig.3.Influence of trench length.

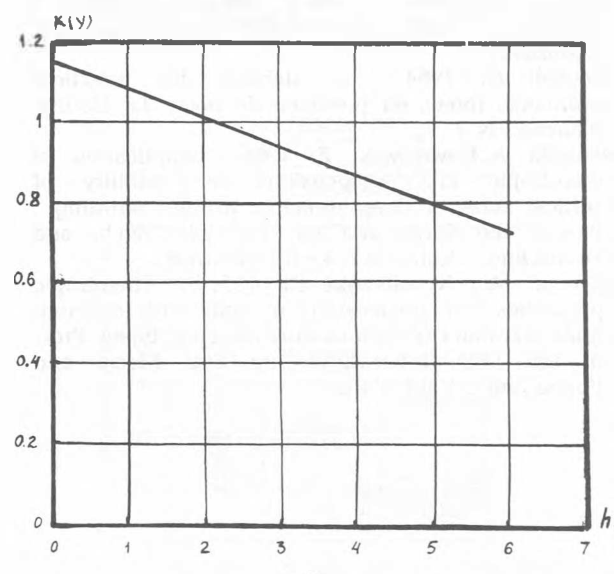

Fig.4. Influence of level of mortal in the trench.

of the moments of these forces was taken into account in the safety margin [safety coeffcient] by doubling of F in the formula [7]. Accounting a linearity of law of distribution of bentonite mortar pressure [unit weight $-\gamma_{bm}$] and water [unit weight $-\gamma_w$] with depth we receive the design formula from the expression [7] :

$$K_{st} = \frac{\gamma_{bm}(h-h_1)^2}{4F/l+\gamma_w(h-h_0)^2} \quad [8]$$

If the condition $K_{st} > 1$ takes place , then the given area of trench is considered to be stable.

The algorithm and the computer program were worked out to determine such areas of initial parameters , when soil resistance to sliding on the surface of collapse may be insufficient. The calculations determine the least value of unit weight and the level of bentonite mortar , ensuring stability of trench at the given conditions. The examples of calculations are given in the Tables 1−3 and in the Fig.3,4.

The numerical analysis of action of some parameters showed , that stability of trench is increased to a large extent with increase of unit weight of bentonite mortar and angle of internal friction of soil as well as it cohesion. This stability is increased also with lowering of level of ground waters. The falling of level of mortar in trench [even nonconsiderable] is the most dangerous fact for stability . Coefficient of stability is characterised by nonlinear damping function . Increase of depth of trench causes nonlinear increase of coefficient of stability , approaching asymptote . As a result , beginning with some depth , its further increase does not lead to the significant decrease of coefficient of stability . The dependence of coefficient of stability on the length of trench is very important and is a linear – decreasing one . The action of coefficient of dynamics on the decrease of safety factor does not exceed 10% in the range of soil vibrations due to subway trains movement .

The calculations that were made as applied to the construction of underground structure on the Manezhnaya Square in Moscow , showed the possible zones of nonstability of trench in it upper part , where comparatively weak interlayers of the Quaternary deposits of soil [dusty sands] are occured . After sinking them through the walls of trench are stable along the whole length up to 39 m. with the maximum level of bentonite mortar .

If we have nonhomogeneous soils in the body of collapse , then the differences of their unit weight should be taken into account . If we have the inclined surface of sliding , then the weighted average values of angle of internal fricton and cohesion should be taken into account .

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