Application of Thixotropic Clay Suspensions for Stability of Vertical Sides of Deep Trenches without Strutting

Utilisation de suspensions d'argile thixotropique pour stabiliser les parois verticales de tranchées non étayées

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SUMMARY

The paper describes investigations on the applicability of thixotropic clay suspensions for deep trench excavations without strutting, for vertical watertight cut-off walls. Some results of theoretical and laboratory investigations on the stability of vertical sides of trenches filled with suspensions are presented. The results of investigations are compared with field observations carried out on an experimental plot where 9 trenches from 7 to 26 m deep were executed. Activation of ordinary clays used for thixotropic suspensions is also described.

SOMMAIRE

On décrit, dans cette communication, les recherches faites sur la possibilité d'utilisation de suspensions d'argile thixotropique en vue de l'excavation de tranchées profondes non étayées pour la réalisation de murs parafouilles. On présente une analyse théorique et quelques résultats de laboratoire sur la stabilité des parois de tranchées verticales remplies de cette suspension. Les résultats de l'analyse sont comparés à ceux obtenus d'essais en chantier faits à une échelle expérimentale sur 9 excavations dont la profondeur variait de 7 m à 26 m. On décrit aussi l'activation des argiles ordinaires pour les utiliser comme suspensions.

RECENTLY THE AUTHORS CARRIED OUT some investigations on the applicability of clays for construction of vertical watertight cut-off walls employed in civil engineering and water works practice. Watertight barriers were built of cohesive soils in cut-off trenches excavated without strutting by clamshell excavators and draglines, using thixotropic clay suspensions. Hydrostatic lateral pressure exerted by the suspension protected the sides of the trench against slides. These investigations also included the execution of nine experimental trenches up to 26 m deep and up to 44 m long (Table I). Soil conditions at the experimental site are shown in Fig. 1.

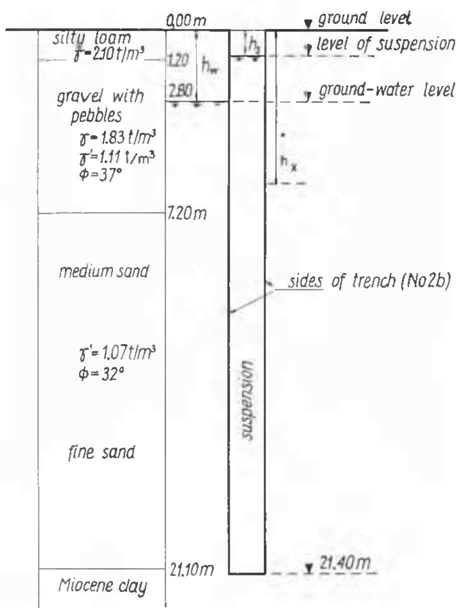

FIG. 1. Soil profile, trench no. 2b.

Unit weight of the suspension needed for stability of the sides of the cut was determined by equating lateral unit pressures acting on the plane of the side as exerted by the suspension and by the ground (Piaskowski, 1964).

$$p_z - p_w - p_a \geqslant 0, \qquad (1)$$

and

$$p_z = \gamma_z(h_x - h_s) \qquad (2)$$

$$p_w = \gamma_w(h_x - h_w), \qquad (3)$$

and for $h_x \leqslant h_w$:

$$p_a = \gamma K_A h_x, \qquad (4a)$$

and for $h_x > h_w$:

$$p_a = \gamma K_A[h_w + (h_x - h_w)\gamma'/\gamma], \qquad (4b)$$

where p_z = hydrostatic pressure of clay suspension; p_w = hydrostatic pressure of groundwater; p_a = active earth pressure of soil skeleton; γ_z = unit weight of suspension; γ_w = unit weight of water; γ = bulk density of soil above groundwater level; γ' = unit weight of submerged soil (i.e., below groundwater level); h_x, h_w, h_s, as shown in Fig. 1; K_A = coefficient of active lateral earth pressure.

Because the ground of the experimental plot consisted mainly of cohesionless soil and the length of the cuts was comparatively large in comparison with their depth, K_A may be defined thusly (after Coulomb):

$$K_A = \tan^2(45° - \phi/2). \qquad (5)$$

The influence of length L of the cut on the value of K_A was investigated theoretically (Kowalewski, 1964). It was

TABLE I. SOME DATA CONCERNING 9 EXPERIMENTAL TRENCHES (PIASKOWSKI, 1964)

Number of trench	Size of trench: depth (m)	Size of trench: length (m)	Mean unit weight of suspension supplied to the trench	Content of Na_2CO_3	Specific gravity of suspension in the trench: Range of particular values	Mean values	Values computed from formula 6†	Computed values of factor of safety
1	7.3	13.0	1.135	3.8	1.195–1.220	1.207	1.101	1.26
2a*	14.7	28.0	1.150	3.3	1.255–1.322	1.310	1.244	1.17
2a*	14.7	28.0	1.150	3.3	—	1.291	1.244	1.12
2b*	21.4	43.0	1.142	3.5	1.240–1.295	1.281	1.296	0.96
2c*	25.9	44.0	—	—	1.160–1.313	1.277	1.295	0.95
3	7.9	23.0	1.122	3.5	1.135–1.170	1.152	1.067	1.23
4	8.0	23.0	1.124	3.5	1.175–1.210	1.194	1.088	1.27
5	8.0	14.7	1.133	3.5	1.155–1.178	1.166	1.069	1.25
6	8.0	20.0	1.160	3.5	1.198–1.215	1.209	1.095	1.30
7	7.0	8.5	1.145	3.5	1.230–1.272	1.252	1.080	1.43
8	8.0	14.5	1.140	3.5	1.170–1.275	1.251	1.055	1.48
9	16.0	30.0	—	—	1.298–1.512	1.412	1.278	1.36

*Cuts marked 2a, 2b, and 2c are successive stages of excavation of the same cut of final depth 25.9 m
†Unit weights required for stability of walls of cuts were computed from formula 6 assuming the properties of soils given in Fig. 1.

assumed that arching might occur in a cut of a small length (Fig. 2), assuming conditions analogous to those for determining the vertical pressure acting on the crown of a tunnel. Using Coulomb's method and assuming that the sliding wedge has the shape of a segment of a vertical parabolic cylinder ABC—A′B′C′ and that sliding occurs on the plane A′B′C′ which is inclined at a known angle α to the ground level we obtain equations enabling us to plot nomograms for determination of K'_A values for trenches of small length. An example of such a nomogram concerning the case $\gamma' : \gamma = 0.57$ and $\phi = 35°$ is shown in Fig. 2. It is seen in Fig. 2 that K'_A decreases considerably compared with

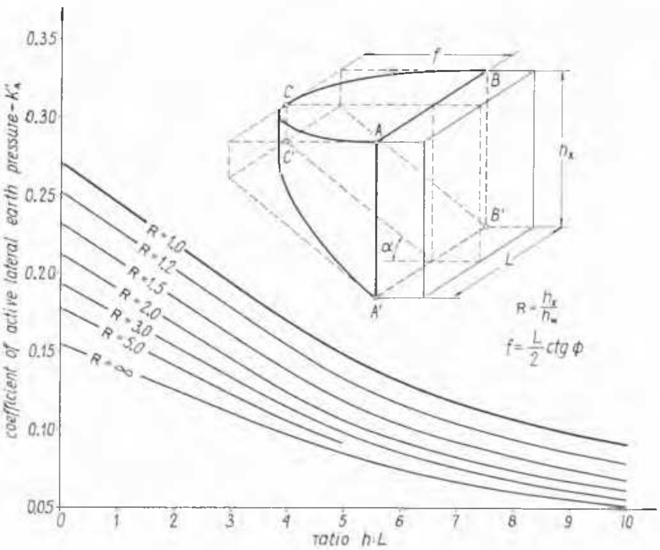

FIG. 2. Variation of active earth pressure coefficient with trench dimensions.

K_A obtained from Eq 5 when the length L of the cut decreases, i.e. the ratio $h : L$ is increasing. Therefore a lower value of γ_z is needed for stability of short trenches than that for stability of long ones; in one of the analysed cases (homogeneous subsoil; depth 15 m) some data of the dependence $\gamma_z = f(L)$ are as follows: $L = 5.0$ m, $\gamma_z = 1.174$ gram/cu cm; $L = 10.0$ m, $\gamma_z = 1.216$ gram/cu cm; $L = 15.0$ m, $\gamma_z = 1.234$ gram/cu cm; $L = \infty$, $\gamma_z = 1.266$ gram/cu cm.

The most common practical cases are those in which inequality (1) is satisfied in the range $h'_c \leqslant h_x \leqslant h_c$ and the formulae for h_c and h'_c are obtained from Eqs 1 to 4.

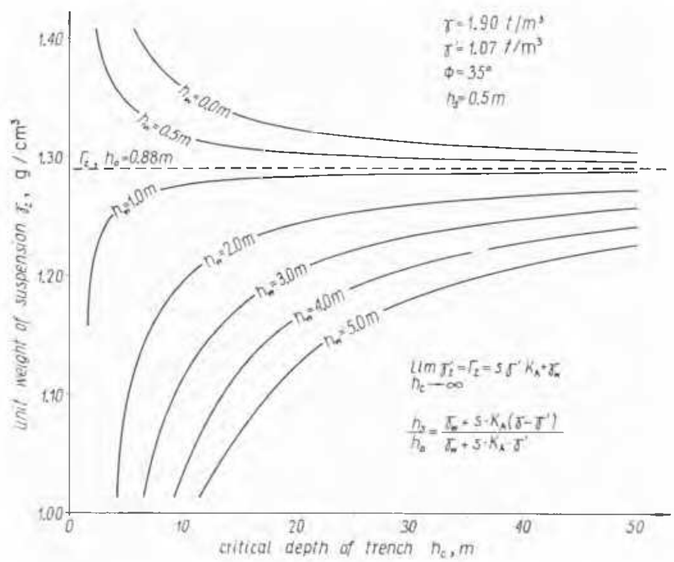

FIG. 3. Unit weight of suspension *vs* critical depth of trench.

Fig. 3 shows the dependence of the value γ_z on the critical depth h_c by various groundwater levels h_w. According to this diagram we have:

(a) For the values $h_w < h_0$, the values γ_z decrease when the depth h_c of cut increases; this dependence is inverse when $h_w > h_0$.

(b) The asymptote of the function $\gamma_z = f(h_c)$ in both the above-mentioned cases is a line parallel to the h_c axis. Moreover in given water and soil conditions and for a determined value h_s there is a certain value h_0 when $\gamma_z = \Gamma_z$ = constant for any arbitrary value h_c.

Fig. 3 shows a great influence of groundwater level on stability of sides of trenches filled with suspension.

The subsoil of the experimental plot was a multi-layered one, and therefore the required unit weight of suspension γ_z was determined for the depth $h_m = h_c$ (Fig. 1) using the formula:

$$\gamma_z = \frac{K_A}{h_m - h_s}\left[\sum_{i=1}^{k} \Delta h_i \gamma + \sum_{i=k+1}^{n} \Delta h_i \gamma'\right] + \left[\frac{\gamma_w(h_m - h_w)}{h_m - h_s}\right]. \quad (6)$$

The suspension used had unit weight $\gamma'_z > \gamma_z$ and a formula for calculating the coefficient of safety was proposed (Piaskowski, 1964):

$$s = \frac{\gamma'_z(h_m - h_s) - \gamma_w(h_m - h_w)}{\gamma_z(h_m - h_s) - \gamma_w(h_m - h_w)}. \tag{7}$$

The necessity of using a coefficient of safety results, among other reasons, from the difficulty in obtaining the required data about soil conditions; one must, however, avoid the use of excessive values for γ'_z because high hydrostatic pressure of the suspension may cause (in certain conditions) difficulties for the excavators. Moreover, there is undoubtedly, in the calculations, a certain margin of safety because satisfactory stability of the sides of the trenches was obtained at values of s practically equal to one or even with some less than one (Table I).

The data concerning nine experimental trenches are presented in Table I. As the cuts were to be filled with cohesive soil and not with concrete, their width was relatively large and amounted to 0.9–1.4 m (depending upon the kind of excavating equipment). The mean unit weight of suspension in the cuts was checked by taking samples from different levels; the values γ_z given in the fourth column are the weighted means.

In all nine cases, stability of sides of the trenches was excellent; cut 2a with the depth 14.7 m was filled only with suspension for 9 months and no slides occurred. Good stability of the sides was caused undoubtedly by the excellent stability of the suspension. Its unit weight virtually did not diminish, because of sedimentation of sand particles and the mean values of γ_z at different times T are as follows (data for cut 2a, 14.7 m depth): $T = 16$ days, $\gamma_z = 1.310$ gram/cu cm; $T = 149$ days, $\gamma_z = 1.297$ gram/cu cm; $T = 247$ days, $\gamma_z = 1.291$ gram/cu cm; $T = 261$ days, $\gamma_z = 1.291$ gram/cu cm.

It was found that suspension supplied to the cut during its excavation may have a unit weight much smaller than the one required for stability of sides of the cut (Table I, column 8). The density of suspension in the cut increases because it becomes sandier by mixing with the excavated soil (muck). The degree of this sanding (i.e., for instance the size of particles of muck remaining in the suspension) may be controlled in a wide range by changing properties of the suspension supplied to the cut (Piaskowski, 1964). Generally speaking, sanding of the suspension depends on the following factors: (*a*) structural shear strength τ_s of the suspension used; (*b*) method of excavation, and type of equipment used; (*c*) grain size distribution of the subsoil; (*d*) methods of handling the suspension (separating it from muck, etc.).

Fig. 4 illustrates dependence of the mean unit weight of suspension (sanded) in the cut on the unit weight of suspension supplied to the cut during excavation; numbers at particular points of the diagram correspond to the numbers of cuts given in Table I and only these cuts were taken in consideration where standardized handling of suspension was carried out.

TABLE II. SOME PROPERTIES FOR MIOCENE CLAY USED FOR SUSPENSIONS IN FIELD RESEARCH WORKS

Soil characteristics	Values for particular samples	Mean values
Specific gravity (grams/cu. cm)	2.72–2.78	2.75
Content of particles 0.05–0.002 mm (per cent)	26–34	30
Content of particles <0.002 mm (per cent)	59–70	66
Plastic limit (per cent)	27.5–28.9	28.6
Liquid limit (per cent)	89.7–101.5	95.0
Colloidal activity (after Skempton)	0.97–1.06	1.01
Stiffness limit (per cent)	221–301	271
Content of:		
SiO_2 (per cent)	—	59.20
Al_2O_3 (per cent)	—	24.74
Fe_2O_3 (per cent)	—	3.96
TiO_2 (per cent)	—	0.91
Loss of ignition (per cent)	6.69–7.70	7.30

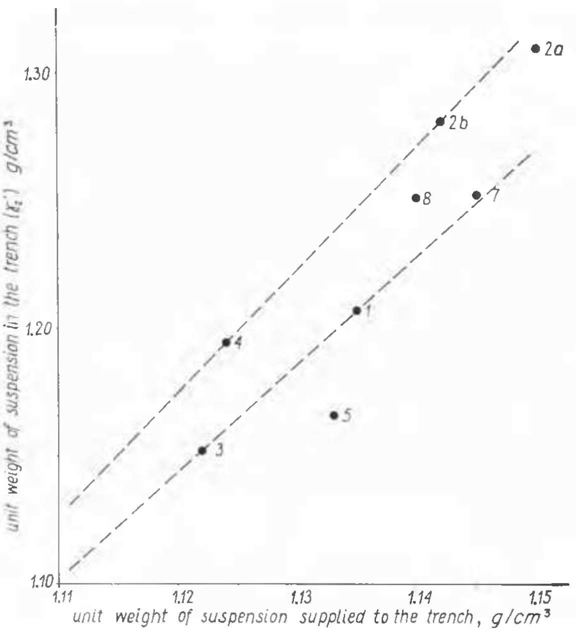

FIG. 4. Variation in unit weight of suspension after placement in trench.

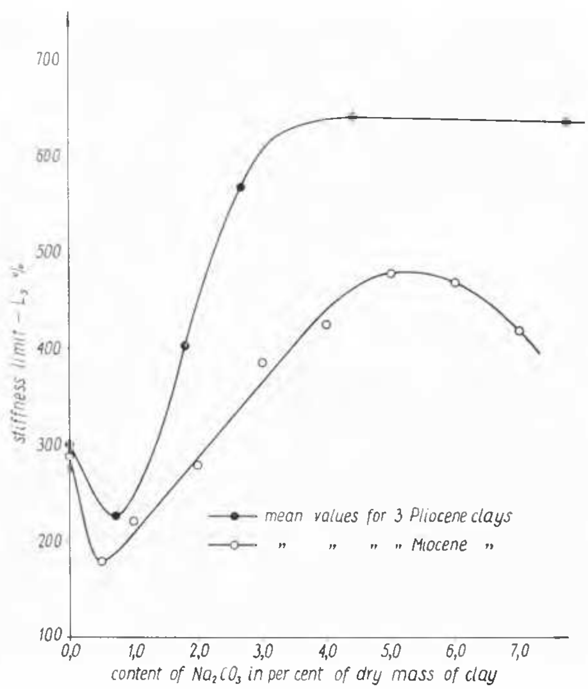

FIG. 5. Stiffness limit *vs* percentage of NA_2CO_3 additive.

Miocene clay was used for suspensions. It was illitic, with a possible content of minerals belonging to the montmorillonitic group (endothermal minimum at +850 − 860 C). The properties of this clay are shown on Table II.

An admixture of Na_2CO_3 improved the thixotropic properties of the suspension by increasing its structural shear strength τ_s. This problem has been investigated by Institute of Building Technics since 1952 (Piaskowski, 1956, 1964). Several investigations of different methods of activating ordinary illitic and illite-montmorillonitic clays were carried out and the influence of different chemical agents on the various properties of suspensions was determined. Fig. 5 shows, for example, the dependence of stiffness limit (Piaskowski and Kowalewski, 1961) values L_s of the Miocene and Pliocene clays on the amount of Na_2CO_3 added. This relationship has two extremities: (*a*) minimum of thixotropic properties when admixture of Na_2CO_3 is about 0.3–0.8 per cent; (*b*) maximum of thixotropic properties when admixture of Na_2CO_3 is 5.0–5.6 per cent (for Miocene clays) of dry mass of clay in suspension.

Stiffness limit was determined by the "inverted test-tube method" (Piaskowski, 1956, 1964; Piaskowski and Kowalewski, 1961). In this method the measuring standard for thixotropic properties is the moisture content of the thoroughly stirred suspension at which, after 5 minutes' stiffening time, the suspension reaches a sufficiently large τ_s value, and no longer flows under its own weight when the test tube (15-mm diameter) is turned upside down.

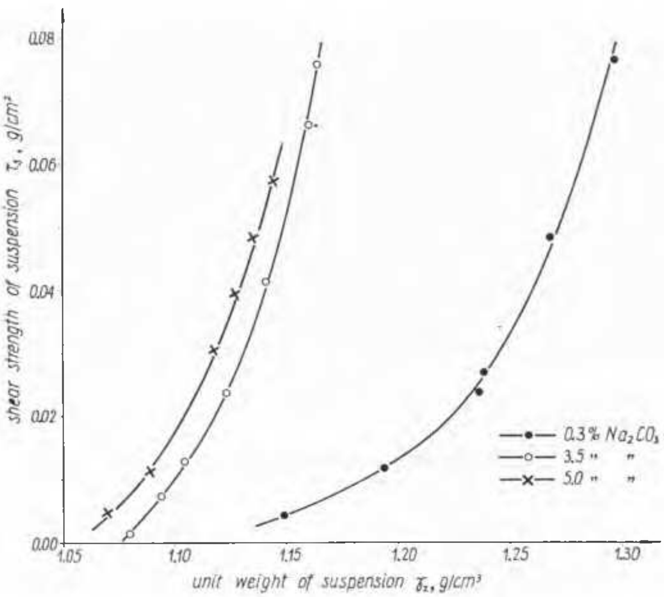

FIG. 6. Shear strength of suspension *vs* unit weight suspension.

Changes of L_s values are indicated by the shape and parameters of dependence $\tau_s = f(\gamma_z)$. Fig. 6 shows, for example, the discussed relationship for suspensions of Miocene clays at various admixtures of Na_2CO_3. The investigations were carried out with rotary apparatus SNS-2 (equipped with torsion wire) and the measurements were taken every two minutes after thorough stirring of a given suspension. The curve (Fig. 6) at the extreme right corresponds to a minimum of thixotropic properties and, using optimum admixtures of Na_2CO_3, it is possible to obtain suspensions having given values of τ_s at the smallest unit weight γ_z. In this way an admixture of activating agents allows reduction of the amount of dry mass of clay used per unit of suspension with the required shear strength τ_s. The determined shear strength, however, is necessary for sufficient stability of suspension and its ability to become sandy (Fig. 4).

It must be pointed out that various soils are liable to activation in different degree. Investigations carried out on diluvial, Pliocene, and Miocene clays showed that the coefficient of relative increase of the value L_s is equal to 1.54 − 4.01 when the optimal admixture of Na_2CO_3 is 3.5–8.0 per cent. Seventeen clays of different geological origin and of various grain size distributions were investigated (Piaskowski, 1964) but a definite relation between ability of thixotropic activation of clay and its mineralogical type could not be established, although it was found that Pliocene clays show the greatest mean coefficient (equal to 2.73) of relative increase of value L_s and that this coefficient is much smaller for diluvial and Miocene clays (1.96 and 1.77 respectively). It was found also that it does not pay to improve the properties of suspensions of natural bentonite by activating them with a cold solution of Na_2CO_3. It confirms that bentonite must be adequately prepared in a factory, making it a product of high quality, although rather expensive. Using the ordinary clays activated by the method discussed one must take 150–200 kg of dry mass of clay for 1 cu m of suspension instead of 60–100 kg of activated bentonite, but the cost of material for the suspension is much less.

REFERENCES

KOWALEWSKI, Z. (1964). Parcie czynne gruntu w wykopie o skończonej długosci. *Biul. Inf. Nauk.-Techn. ITB* (Warszawa) (to be published).

PIASKOWSKI, A. (1956). *Prace Instytutu Techniki Budowlanej*, Nr 228, Warszawa.

——— (1964). Tiksotropowe zawiesiny gruntowe i ich zastosowanie przy wykonywaniu ścianek szczelnych i oporowych. *Prace Instytutu Techniki Budowlanej*, Warszawa.

PIASKOWSKI, A., and Z. KOWALEWSKI (1961). Thixotropic properties of suspensions of soils with different grain sizes and of various mineralogical types. *Proc. Fifth International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, pp. 293–6.