

# ESTIMATION OF INTERPARTICLE DISTANCES AND LONG-RANGE PARTICLE INTERACTIONS IN SATURATED CLAYS

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## INTRODUCTION

Soil mechanics was considering by now the relations between certain parameters. Correlations found for a given soil not always have a general character and certain soils behave sometimes in a quite unexpected manner. As now the knowledge in soil physics, is much more profound it is necessary to establish the physical reasons of the considered processes.

In this paper we shall investigate the mechanical processes. The applied external load is counteracted by internal forces. There are indications that in the clay water system these forces may be presented schematically as in the Fig. 1 and divided into two groups:

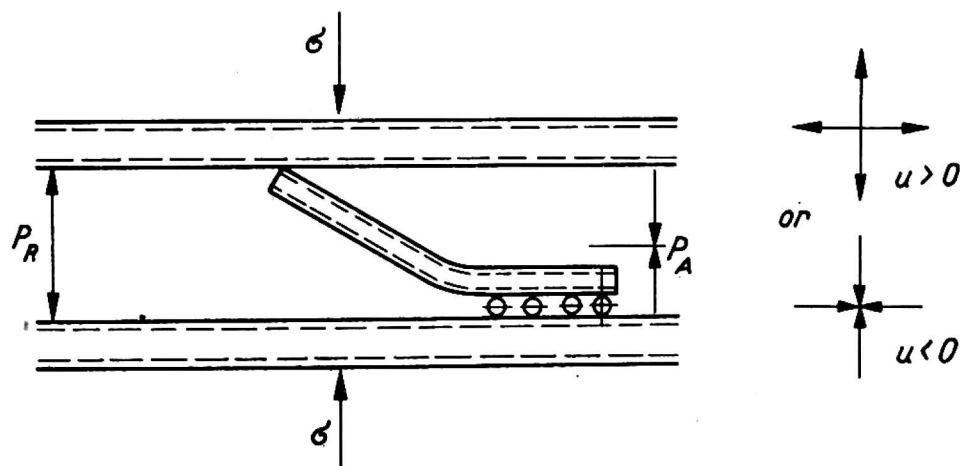


Fig. 1. Physical forces in clay-water system

1. Contact forces acting in places of direct contact of clay particles:
  - a) primary valence bonds causing the particle cementation and the elasticity of crystallites,

- b) secondary valence bonds (van der Waals bonds, hydrogen bonds),
  - c) edge-to-face attraction,
  - d) ionic lattice attraction.
2. Long-range forces:
- a) diffuse layer repulsion pressure  $p_R$ ,
  - b) London - van der Waals dispersion attraction pressure  $p_A$ .

The consideration of the mechanism of these forces indicates, that the frictional component of the shear strength is due to contact forces. This component is proportional to the normal load in the shear plane. It is a generally accepted opinion, that on this load depends the surface area of the real contact between interacting bodies and thus the number of bonds and the energy necessary to break them.

The estimated for kaolinite shear strength due to primary valence bonds, assuming a linear contact between particles by a mono-atomic line, was 0.063 kG/cm<sup>2</sup>. This value for secondary valence bonds would be about one order of magnitude smaller. The edge-to-face attraction take some part in the shear strength of kaolinite where this force has a nonnegligible value and it is probably a structure forming factor. The calculated ionic lattice attraction is of the order of 10<sup>3</sup> kG/cm<sup>2</sup>. It is probable that this force takes part in the shear strength, but the surface area of its action creates only a small fraction of the total shear plane.

#### LONG-RANGE INTERACTIONS

The shear strength may be divided into the frictional component, proportional to the normal load, and cohesion component independent of the normal load. It may be assumed that this component is due to long-range interactions.

In the saturated clay-water system the long-range interactions are the diffuse layer repulsion pressure  $p_R$ , and the London-van der Waals dispersion attraction pressure  $p_A$ .

The diffuse layer interaction is due to the presence of the negative crystal lattice charge of clay minerals. This negative charge is neutralized by exchangeable cations, which in water form a diffuse layer due to the kinetic energy of thermal movements. If the interparticle distance  $2d$  is greater than the double range of one diffuse layer, then between the particles diffuse layer repulsion is acting of a character similar to the character of the osmotic pressure. For two parallel plates the diffuse layer repulsion pressure  $p_R$  may be calculated from the theoretical equation:

$$p_R = 2 n k T (\cosh Y_d - 1). \quad (1)$$

Here

$$Y_d = \frac{Ze\psi_d}{kT} = 2 \ln \frac{\pi}{\kappa(d + x_0)} \quad (2)$$

is the dimensionless parameter of the electric potential  $Y_d$  in the middle between the clay particles separated by the distance  $2d$  ( $x_0$  is a correction of the order of 1 to 3 Å),

$n$  — the cation concentration,

$k$  — the Boltzmann constant,

$T$  — the temperature in °K,

$Z$  — the valence of exchangeable cation,

$e$  — the elementary charge of the electron,

$\psi_d$  — electric potential in the middle between plates,

$$\chi = \sqrt{\frac{8 \pi n e^2 Z^2}{\epsilon k T}},$$

$\epsilon$  is the electrostatic dielectric constant.

Thus between the diffuse layer repulsion pressure and the interparticle distance there exists a given logarithmic relation

$$p_R = f(\ln d). \quad (3)$$

All the values necessary to calculate  $p_R$  for the clay-water system may be easily measured or calculated except the interparticle distance  $2d$ . This value may be measured directly only for certain idealized systems. The same value is necessary to calculate London-van der Waals dispersion untraction pressure

$$p_A = -\frac{C_{scl}}{\bar{\epsilon}^2(\omega)} \left\{ \frac{1}{d^3} + \frac{1}{(d + \delta)^3} - \frac{2}{\left(d + \frac{\delta}{2}\right)^3} \right\}, \quad (4)$$

where  $C$  is a constant depending on the properties of atoms in the crystal lattice of interacting bodies,

$\bar{\epsilon}(\omega)$  is the effective optical dielectric constant of the medium through which the interaction occurs,

$s_{cl}$  is the coefficient of many-body interaction between clusters (particle assambles).

Thus after summation over all the atoms of two interacting bodies the relation is obtained between the interaction pressure and the third power of the distance

$$p_A = -f(d^{-3}) \quad (5)$$

and not the seventh power of the distance as it is true for interaction force between individual atoms.

A more detailed discussion of the London-van der Waals interaction is given in the second paper of this series.

#### ESTIMATION OF INTERPARTICLE DISTANCE

Interparticle distance may be measured directly only in idealized systems composed of particles oriented parallel to each other and rather thin. Then the X-ray diffraction measurements may be applied, what was done by Norrish and Rausell-Colom [5], who obtained for a certain system quite a good agreement between the measured swelling pressure and the calculated diffuse layer repulsion pressure  $p_R$ .

In real systems the interparticle distance may be estimated only indirectly.

Norrish [4] found a straight linear relation between the water content  $W$  and interparticle distance  $2d$  for water contents exceeding a certain value. Thus for clays of small particle size not containing the macropore water (e.g. capillary water) there may be assumed

$$d = \frac{W - W_c}{\bar{S}\rho}, \quad (6)$$

where  $W_c$  is the crystal phase water of the properties differing from properties of the free liquid water. This is the water sorbed on the external particle surface and in the intersheet space.

$\bar{S}$  — is the external particle specific surface,

$\rho = 1.0 \text{ g/cm}^3$  is the free liquid water density.

It seems that the best method of estimation of the crystal phase water is to measure the water sorption at the given conditions of the relative vapour pressure. The consequence of such a choice is to determine also the external specific surface  $\bar{S}$  from the water sorption measurement. This last mentioned value may be determined also by other methods, but none of them is satisfactory and the sorption test proposed gives the results which are not worse than other method test results.

The literature data indicate [1] that at  $p/p_0 = 0.5$  and  $25^\circ\text{C}$  on the external surface of kaolinite there is forming a 1.9 molecular layer of water molecules. Thus it was assumed it to be also true for other clay minerals and to be possible to neglect at these conditions the intersheet water sorption in K-clay. Basing on these assumptions the external specific surface could be calculated from the water sorption of K-clay at  $p/p_0 = 0.5$  [ $W_a$  (K; 0.5)]

$$\bar{S} = \frac{W_a(K; 0.5)}{1.9 \Phi_{H_2O} \rho_{H_2O}}, \quad (7)$$

here  $\Phi_{H_2O} = 2.76 \text{ \AA}$  is the water molecule diameter,  $\rho_{H_2O} = 1.27 \text{ g/cm}^3$  is the density of the bimolecular sorbed water layer which value was assumed according to Mooney *et al.* and Martin [3, 2]. Results thus obtained gave a good comparison with other test method results but the problem of sorbed water density remains still an open question.

There was found the experimental straight linear relation between the external specific surface  $\bar{S}$ , thus determined and the cation exchange capacity CEC, measured by  $\text{Ba}^{2+}$  cation exchange and X-ray fluorescence analysis. Thus it is proposed to estimate the cation exchange capacity from

$$\text{CEC} = \frac{\bar{S}}{102.4 \text{ m}^2/\text{meq}}. \quad (8)$$

The water sorption test enables also to estimate the internal specific surface  $S - \bar{S}$ , from the water sorption of Mg-clay at  $p/p_0 = 0.5$  (dried at  $200^\circ\text{C}$ ;  $W_m$ ) assuming a determined number of vacancies (10.2 vac. per 24 possible sites) in the bimolecular water layer in the intersheet space, what causes a drop in density to the value  $\rho_{H_2O} = 0.73 \text{ g/cm}^3$ .

$$S - \bar{S} = \frac{W_m(\text{Mg}; 0.5) - W_a(\text{K}; 0.5)}{\Phi_{H_2O} \rho_{H_2O}}. \quad (9)$$

The montmorillonite content index may be estimated as the ratio of the measured internal specific surface to the theoretical specific surface of montmorillonite  $(790 - \bar{S}) \text{ m}^2/\text{g}$

$$M = \frac{S - \bar{S}}{790 \text{ m}^2/\text{g} - \bar{S}}. \quad (10)$$

The comparison of sorption test results with the results obtained by other methods is presented in Table 1.

Table 1

Comparison of clay properties as measured by various methods

Minerals	Sorption test	Other methods
$\bar{S}$ : Z. M. bentonite	117 m <sup>2</sup> /g	114 m <sup>2</sup> /g $\left[ \frac{dQ}{dW} \right]$ 101 m <sup>2</sup> /g $[\delta]$
CEC:		
Z.M. bentonite	1.14 mwal/g	1.31 mwal/g Ba <sup>++</sup>
Ch.C. bentonitic clay	0.798 „	0.825 „
Sedlec Kaolin	0.11 „	0.13 „
Bydgoszcz clay (5)	0.706 „	0.71 „
Bydgoszcz clay (11)	0.525 „	0.50 „
Bydgoszcz clay (13)	0.552 „	0.53 „
M:		
Z.M. bentonite	95.4%	~100%
Lastovce bentonite ( $< 2 \mu$ )	67.6%	70%

Except  $\bar{S}$  the values mentioned above are not necessary to estimate the interparticle distances, but they must be known, when the interactions  $p_R$  and  $p_A$  are calculated.

Another parameter necessary to calculate  $d$  is the crystal phase water  $W_c$ . To determine this value the following conditions were chosen: 2 to 3 week storage at the relative vapour pressure  $p/p_o = 0.95$  assuming the formation of the bimolecular water layer on the external surface and a 3 to 4 molecular layer in the intersheet space. Sorbed water density  $\rho_{H_2O}$  was assumed as equal to 1.27 g/cm<sup>3</sup> and its properties as differing from those of free liquid water (dielectric constant  $\epsilon = 3.0$ ).

Initially it was thought, that after submerging in water the sorbed water properties change to free liquid water properties, as it takes place in anomalous water (polywater). The results presented here indicate, that the crystal phase water content may depend on the storing time and conditions. If the crystal phase water forms a structure, which without vacancies has the density  $\rho_{H_2O} = 1.27$  g/cm<sup>3</sup>, one can imagine that at a given number of vacancies this value may fall to  $\rho_{H_2O} = 1.0$  g/cm<sup>3</sup> or assume intermediate values. The same result is obtained if one assumes, instead of varying water density, the varying number of molecular water layers on the external surface and in the intersheet space, depending on sorption conditions.

The crystal phase water density remains still in the considerations presented an unsolved problem.

It should be mentioned that clay samples stored for about 2 years at  $p/p_o = 0.95$  indicated similar or somewhat smaller water sorption value

than the samples stored at this condition for about 2 weeks (G. Bidlo, personal communication).

Bentonite samples stored for 2 to 3 days at  $p/p_o = 0.95$  sorbed about 1/8 less water than the final sorbed water value.

The choice of the relative vapour pressure  $p/p_o = 0.95$  for the determination of crystal phase water is due to the following facts:

1. In the clay-water system the vapour pressure is decreased and its relative value is close to  $p/p_o = 0.95$ .
2. Above  $p/p_o = 0.95$  the sorption isotherm sometimes increases rapidly and this rise may be due to the capillary condensation.
3. At this vapour pressure condition the anomalous water (polywater) forms in quartz capillaries and its properties are similar to those of clay water.
4. Since years these conditions were used for hygroscopic water content determination.

Thus from the sorbed water content at  $p/p_o = 0.95$  i.e.  $W_a(0.95)$  assuming  $\rho_{H_2O} = 1.27 \text{ g/cm}^3$  the crystal phase water in the clay-water system was estimated either assuming that in both cases the water density is the same (i.e.  $\rho_{H_2O}(\text{sorbed water}) = \rho_{H_2O}(\text{in clay water system})$ ).

$$W_c = W_a(0.95) \quad (11.1.)$$

or assuming that in the investigated clay-water system the crystal phase water indicates the density  $1.0 \text{ g/cm}^3$

$$W_c = \frac{W_a(0.95) 1.0 \text{ g/cm}^3}{1.27 \text{ g/cm}^3} \quad (11.2)$$

The application of numerical factor of formula (11.2.) may be explained also assuming a smaller number of molecular layers of crystal phase water as compared to the number of molecular sorbed water layers at  $p/p_o = 0.95$  (the ratio of these numbers is in eq. (11.2) about 4:5). Further research should indicate the correct interpretation.

Assuming the above mentioned values of the external specific surface  $\bar{S}$  and crystal phase water  $W_c$  it is easy to estimate the long range forces  $p_R$  and  $p_A$ . Here only the London-van der Waals, dispersion interaction pressure  $p_A$  will be discussed.

#### THE COMPARISON OF DISPERSION INTERACTION PRESSURE $p_A$ WITH THE COHESION MEASURED

As it was already told above, the long-range interactions may cause the cohesion of clays, i.e. the component of the shear strength indepen-

dent of normal load. It is not easy to separate this component from the total shear strength of soil in such a way, that it holds a physical meaning. The shear strength was determined in the norwegian type triaxial test with pore pressure measurement at a constant axial strain rate 2%/hour.

After the maximum deviator stress  $1/2 (\sigma_1 - \sigma_3)_f$  was attained and the sample was sheared,  $\sigma_3$  was increased twice and sheared at  $\sigma_3 = \text{const.}$ , thus giving three values of  $1/2 (\sigma_1 - \sigma_3)_f$  at three different values of  $1/2 (\sigma_1 + \sigma_3)_f$  for the same sample. Therefrom the internal friction angle and cohesion were determined. Measurements were performed both in terms of total stresses and in terms of effective stresses. Here the results are presented in terms of total stresses only, as they seem to have a better defined physical meaning and to be better comparable with the long range particle interactions.

Cohesion measurement results were compared with the calculated dispersion interaction pressure  $p_A$ , which is discussed in detail in the second paper.

Tests were performed on Zrecze Małe bentonite, which contained about 95% montmorillonite, therefore they were compared with  $p_A$  values calculated for montmorillonite, assuming the particle thickness  $\delta = 120 \text{ \AA}$ , estimated from half width of their X-ray diffraction peak, the external specific surface  $\bar{S} = 117 \text{ m}^2/\text{g}$  estimated from water sorption test. There was determined the value  $W_a(0,95) = 30.96\%$  and the crystal phase water content was calculated either from eq. (11.1.)

as

$$W_c = W_{a(0.95)} = 30.96\%$$

or from eq. (11.2.) as

$$W_c = \frac{W_a(0.95)}{1.27} = \frac{30.96\%}{1.27} = 24.38\%.$$

It should be mentioned, that the absolute error of the  $W_a(0.95)$  determination amounted to  $\pm 1$  to  $1.5\%$ , and that the weighing of the sample every 1 to 3 days decreased the sorption test result  $W_a(0.95)$  to the value of  $27.4\%$ .

In the Table 2 there is presented the shear strength testing method for particular series. There are also indicated the  $W_c$  values, which gave the best correlation between the measured cohesion  $c$  and the calculated dispersion interaction —  $p_A$ .

From this Table it results apparently, that the  $W_c$  value is not a constant. This conclusion is not finite, as not all the problems are solved yet. It should be kept in mind, that London-van der Waals interactions may



Table 2

## Sample preparation and shearing conditions

Series No.	Sieve in mm	$W_0$ %	Aggregate or paste storage time	Sample preparation	Shearing conditions	$W_f$ %	$W_c$ % at $c \approx PA$	Remarks
I	0.16	50-69	1-2 days	St.C.	$\sigma_{eg}; u=0 = \text{const.}$	50-69	31	
II	1.00	50	1-2 days	St.C.	$u=1, 0 = \text{const.}; B$	53-64	31-35	$tg\beta = 0.061$
III	0.16	54-68	1 day	St.C.	$\sigma_3 = 3, 0; u = u_0 = \text{const.}$	54-66	about 28	$tg\beta = 0.021$
IV	1.00	44-66 47-56	1-3 days	St.C.	$\sigma_3 = 3, 0 = \text{const.}$ or $\sigma_3 = 1, 0 = \text{const.}$	46-60 47-56	24 for $W_f = 46$ to 50%	
V	0.09	45-64	1 day	St.C.	$\sigma_{eg}; u=0 = \text{const.}$	46-63	31 for $W_f = 55$ to 60%	
VIa	1.00	85, 92, 101			$u=0 = \text{const.}$	65-75	about 31	
VIb	1.00	101	1 to several days	N.C.	$u=1, 0 = \text{const.}$	59-76	about 35	$tg\beta = 0, 059$
VII	1.00	94-100	26 days to 2.5 months	N.C. O.C.	$u=0 = \text{const.}$	59-82	35 for $W_f = 61$ to 70%	$tg\beta = 0, 088$
VIII	1.00	93-97	1 to 2 months	N.C.O.C.	$\sigma_3 = \sigma_c = \text{const.}$	61-83	28 for $W_f = 74$ to 82%	other mechanical phenomena (?)
							33 for $W_f = 61$ to 72%	$tg\beta = 0.064$
							28 for $W_f = 80\%$	other mechanical phenomena (?)

not be the only one reason of the cohesion, i.e. in the system there may occur other interactions indicating apparently a higher  $W_c$  value.

On the other hand one cannot exclude yet the possibility that in the bentonite tested the angle of internal friction is constant amounting to about 0.11 and thus the values measured in some test series may be underestimated due to the testing method applied e.g.  $u > 0$  (Table 3). In this case the assumption of the measured value of the internal friction angle would cause the overestimation of the  $c$  values and thus their deviation from the  $-p_A$  calculated. A more detailed analysis is planned and it may indicate, that  $W_c$  changes within smaller limits, than it would result from the Table 2.

For the cohesion measurement results there were calculated the regression lines in form of relation

$$\lg c = -a W_f + b, \quad (12)$$

in term of total stresses (Table 3).

Table 3

Regression lines for the experimentally determined correlation between the cohesion and the water content at failure

Series No.	Equation of regression line	Coefficient of correlation $r_{xy}$	Mean value of $\star$ $\operatorname{tg} \beta = \frac{\Delta(\sigma_1 - \sigma_3)}{\Delta(\sigma_1 + \sigma_3)}$
I	$\lg c = 2.6014 - 0.0424 W_f (W_f = 60 \text{ to } 70\%)$	+0.9325	0.112 $\sigma_x = 0.030$
II	$\lg c = 2.0315 - 0.0309 W_f (W_o = 50\%)$	+0.7748	0.061 $\sigma_x = 0.045$
III	$\lg c = 2.3380 - 0.0397 W_f (W_f \pm 65\%)$	+0.9933	0.021 $\sigma_x = 0.020$
IV	$\lg c = 0.9683 - 0.0139 W_f$	+0.6990	0.110 $\sigma_x = 0.056$
V	$\lg c = 2.2075 - 0.0393 W_f$	+0.9840	0.095 $\sigma_x = 0.020$
VIa	$\lg c = 3.7567 - 0.0572 W_f (W_o = 85, 92, 101\%)$	+0.9751	0.102 $\sigma_x = 0.032$
„	$\lg c = 3.2937 - 0.0508 W_f (W_o = 85, 92\%)$	+0.9451	
VIb	$\lg c = 2.3364 - 0.0352 W_f (W_o = 101\%)$	+0.9887	0.059 $\sigma_x = 0.036$
VII	$\lg c = 3.8184 - 0.0581 W_f$	+0.9738	0.088 $\sigma_x = 0.055$
VIII	$\lg c = 2.9843 - 0.0465 W_f$	+0.9539	0.064 $\sigma_x = 0.038$

\*  $\operatorname{tg} \beta = \sin \phi$  here  $\phi$  is the angle of internal friction,  $\sigma_x$  standard deviation.

The following measurement results for Z. M. bentonite are presented. Static Compacted Samples (St. C.).

Sieved powder (0.09 mm or 0.16 mm or 1 mm) was mixed with water to obtain the assumed water content. The mass was passed through

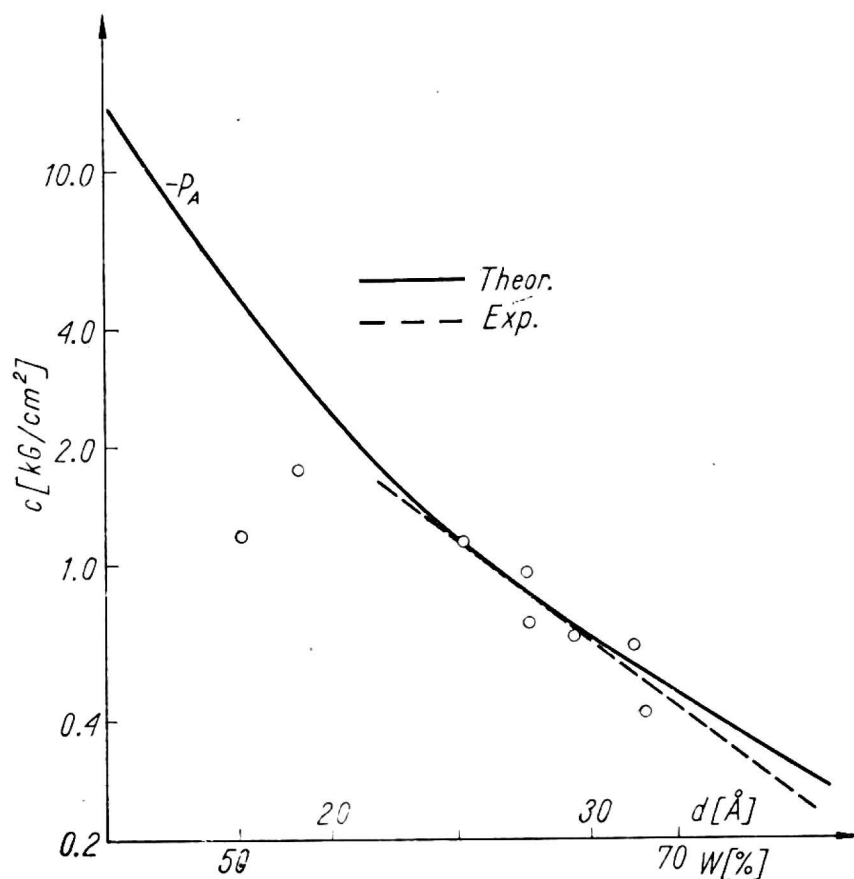


Fig. 2. The measurement results. Series I. St. C.  $W_o = 50-69\%$ ,  $u = 0 = \text{const.}$ ,  $\lg c = 2.6014 - 0.0424 W_f$ ,  $d$  calculated for  $W_c = 30.96\%$

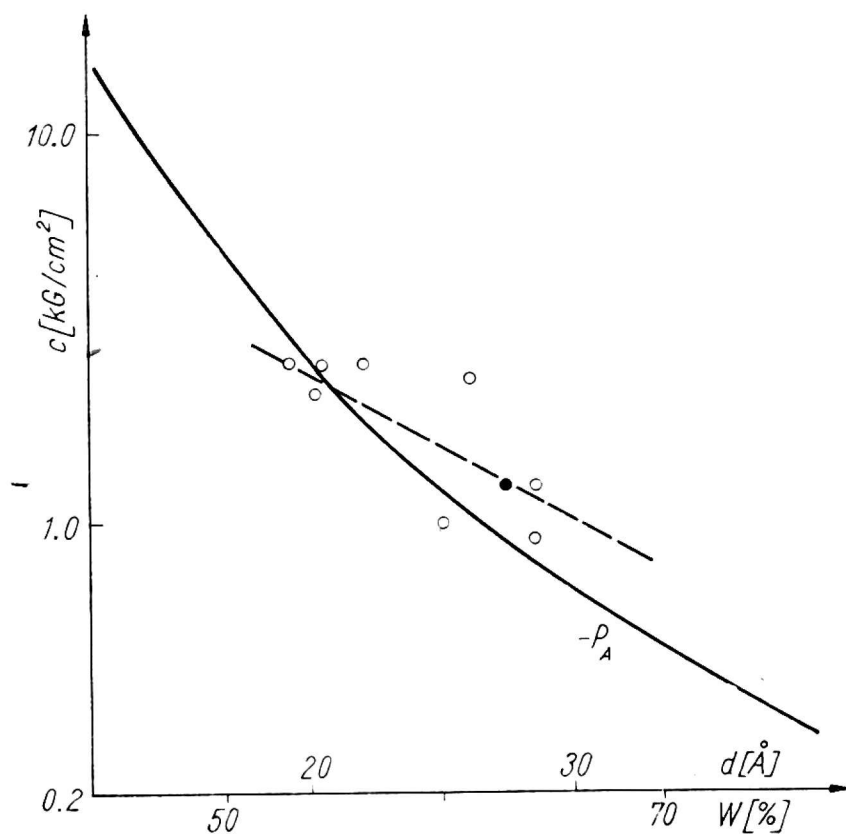


Fig. 3. The measurement results. Series II. St. C.  $W_o = 50\%$ ,  $\bigcirc - W_o = 50\%$ ,  $\bullet - W_o = 61\%$ ,  $u = 1.0 \text{ kG/cm}^2 = \text{const.}$ ,  $\lg c = 2.0315 - 0.0309 W_f$ . Exp. of curves as in Fig. 2

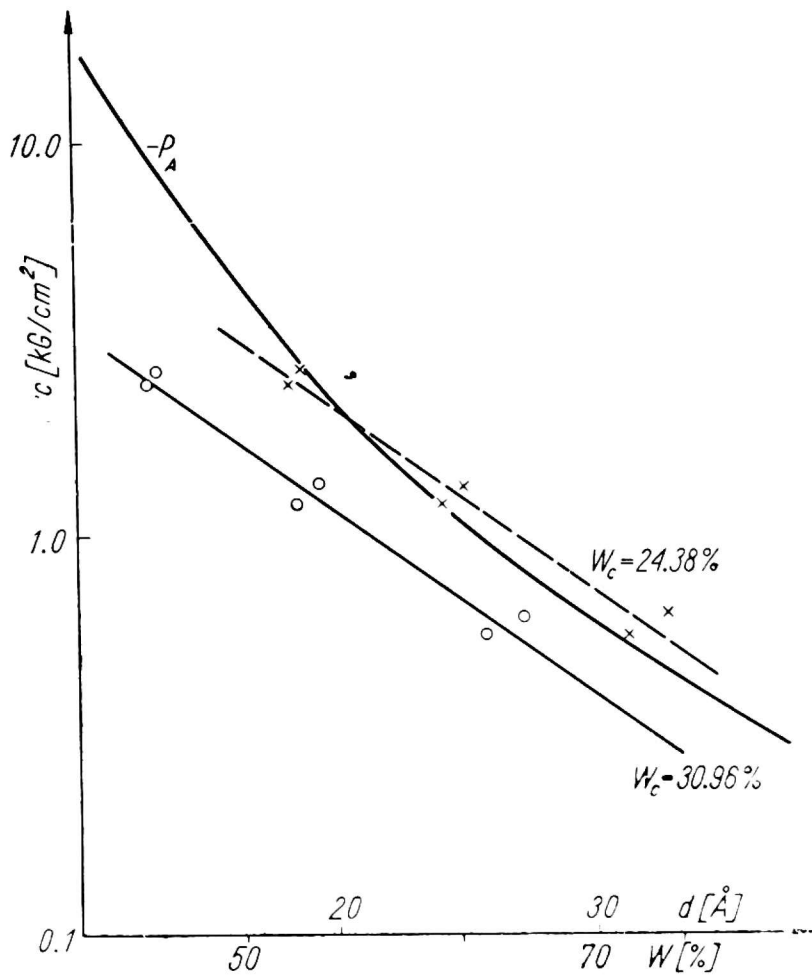


Fig. 4. The measurement results. Series III. St. C.  $W_o = 54-68\%$ ,  $\sigma_3 = 3.0 \text{ kG/cm}^2$ ,  $u = u_o = \text{const.}$ ,  $\lg c = 2.3380 - 0.0397 W_f$ . Exp. of curves as in Fig. 2

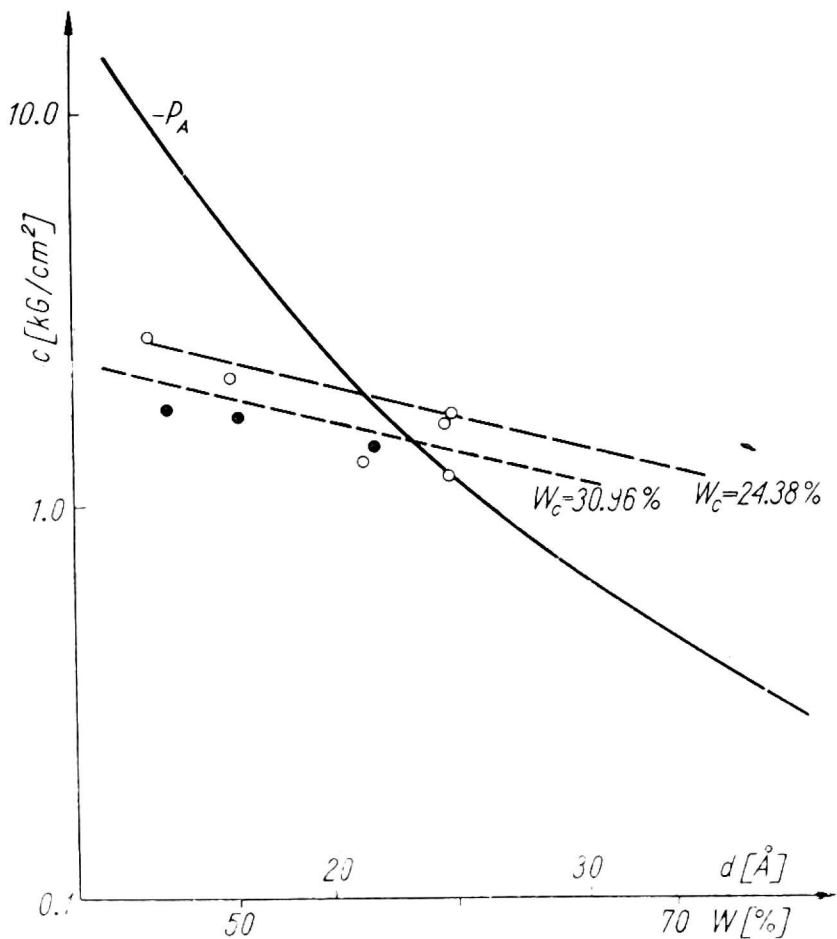


Fig. 5. The measurement results. Series IV. St. C.  $W_o = 44-66\%$ , ● —  $\sigma_3 = 1.0 \text{ kG/cm}^2 = \text{const.}$ , ○ —  $\sigma_3 = 3.0 \text{ kG/cm}^2 = \text{const.}$ ,  $\lg c = 0.9683 - 0.0139 W_f$ . Exp. of curves as in Fig. 2

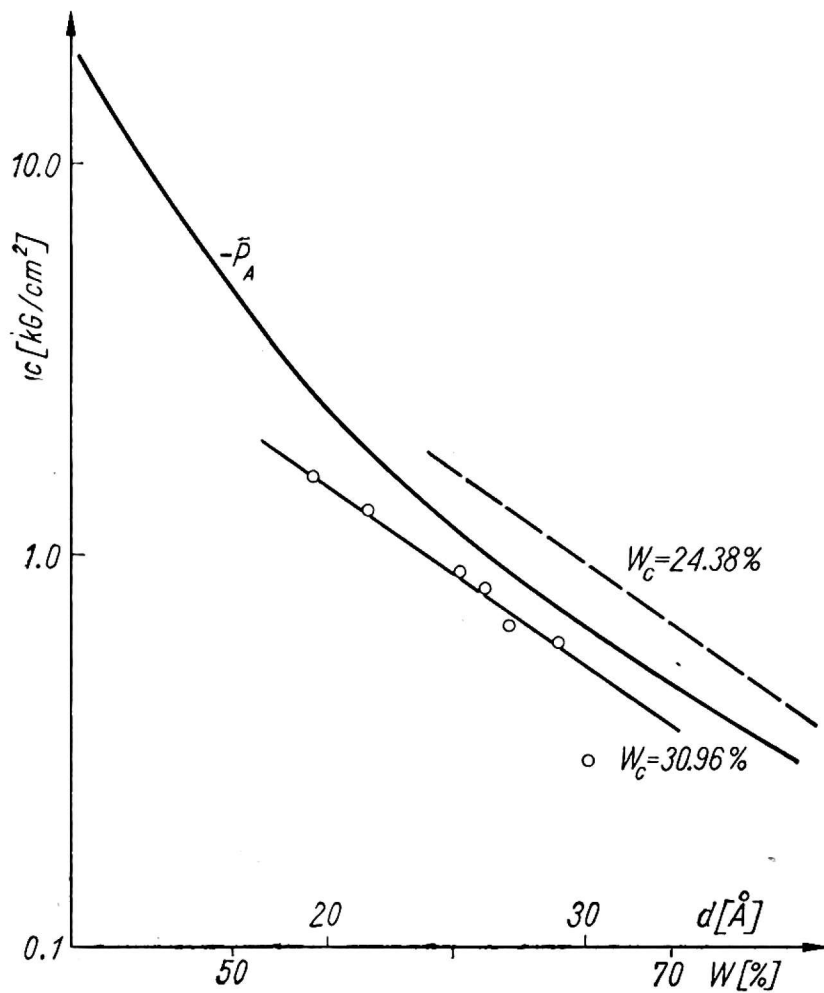


Fig. 6. The measurement results. Series V. St. C.  $W_o = 45-64\%$ ,  $u = 0 = \text{const.}$ ,  $\lg c = 2.2075-0.0393 W_f$ ,  $\circ W_c = 30.96\%$ . Exp. of curves as in Fig. 2

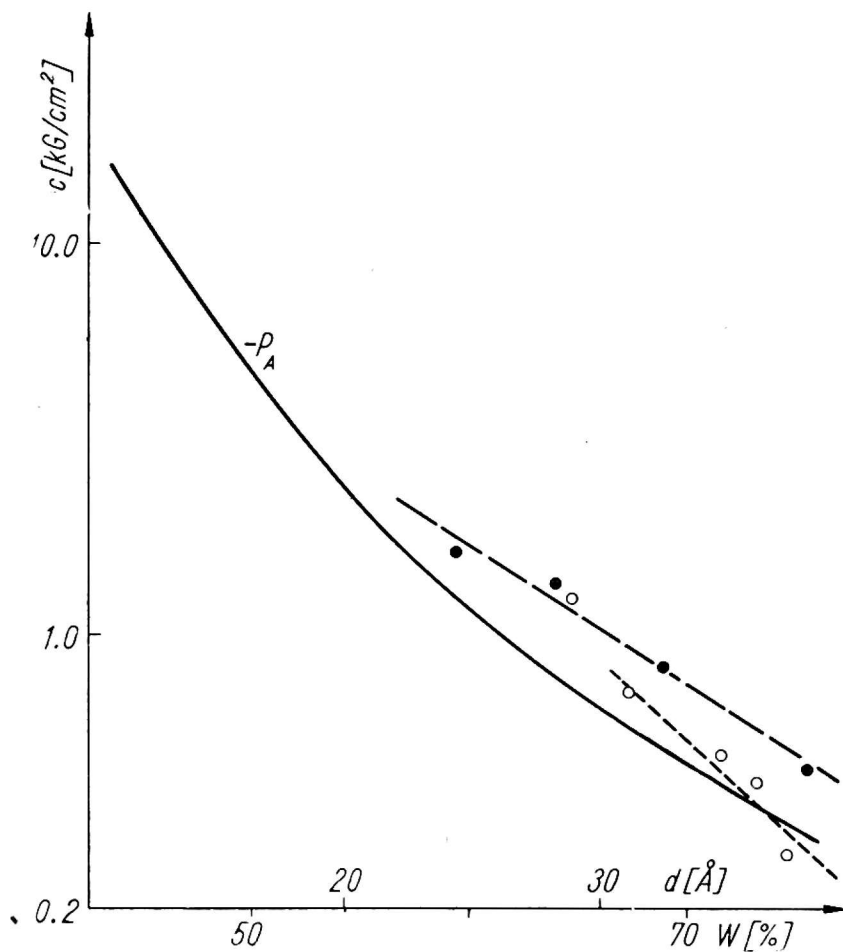


Fig. 7. The measurement results. Series VI a:  $\circ - u = 0 = \text{const.}$ , 1)  $W_o = 85\%$ , 2)  $W_o = 92\%$ ,  $\lg c = 3.2937-0.05081 W_f$ . Series VI b:  $\bullet - u = 1.0 \text{ kg/cm}^2 = \text{const.}$ ,  $W_o = 101\%$ ,  $\lg c = 2.3364-0.03524 W_f$ . Exp. of curves as in Fig. 2

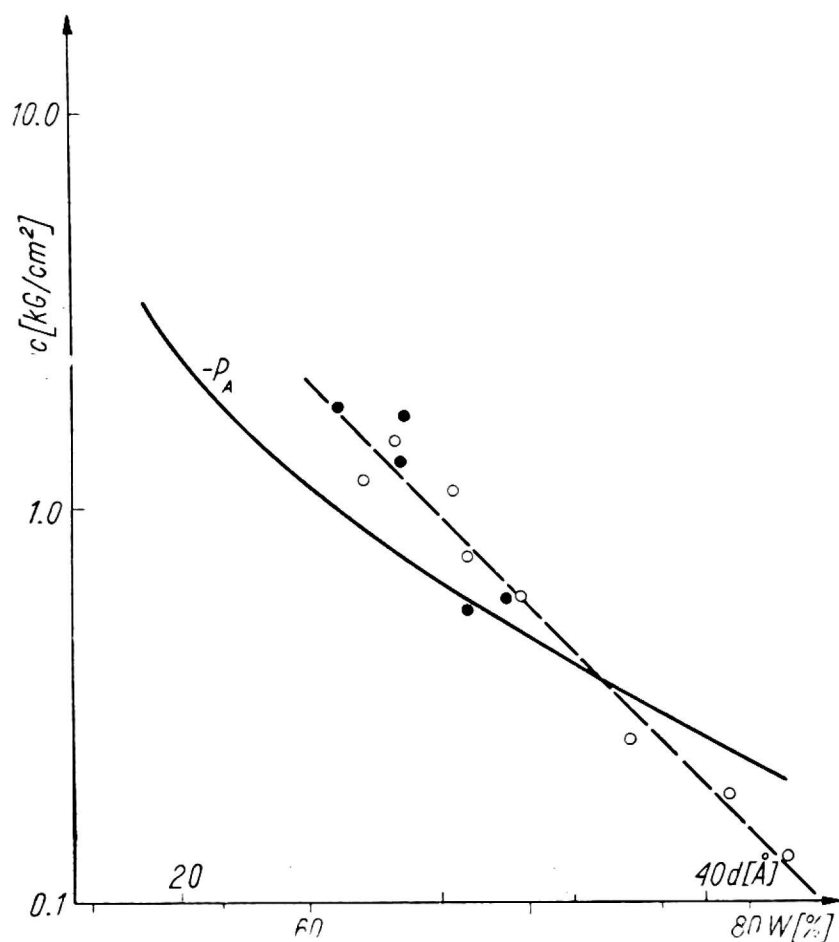


Fig. 8. The measurement results. Series VII.  $u = 0 = \text{const.}$ ,  $\circ$  — N.C.,  $\bullet$  — O.C.,

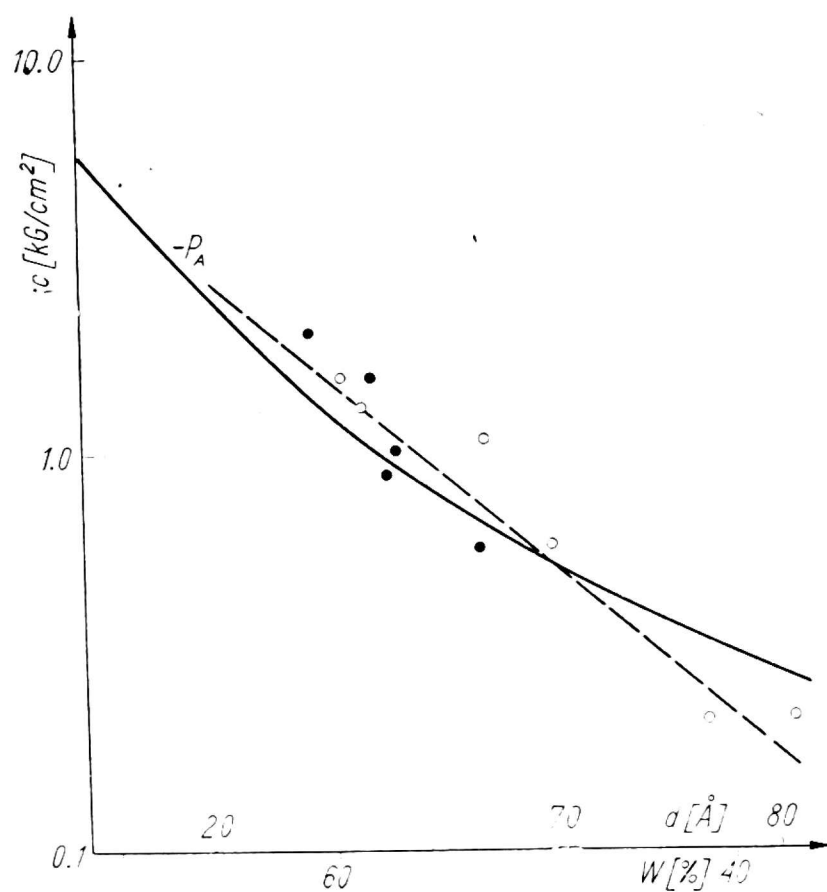


Fig. 9 The measurement results. Series VIII.  $W_0 = 93\text{--}97\%$ ,  $\sigma_3 = \sigma_c = \text{const.}$ ,  $\circ$  — N.C.,  $\bullet$  — O.C.,  $\lg c = 2.9843 - 0.0465 W_f$ . Exp. of curves as in Fig. 2

a 2 mm sieve and left overnight secured from drying out. Static compact (  $W_o = 50$  to  $69\%$  )  $\sigma_3$  was chosen as equilibrium load  $\sigma_1 = \sigma_{3eq}$  in with drainage, then the chosen  $\sigma_3$  (depending on test series) was applied and left overnight without drainage. The angle of internal friction and cohesion were determined during shear test as described above.

**I Series.** Initial water content exceeded the optimum water content (  $W_o = 50$  to  $69\%$  )  $\sigma_3$  was chosen as equilibrium load  $\sigma_3 = \sigma_{eq}$  in which case  $u = 0$  and there was neither water inflow nor water outflow from the sample. Sample was sheared at  $u = 0 = \text{const.}$  (i.e. pore pressure equal to atmospheric pressure) and  $\sigma_3$  was regulated. Water content at failure ranged between  $W_f = 50$  to  $69\%$ . If the cohesion values obtained for  $W_f$  about  $50\%$  were neglected (due to high  $\text{tg } \beta$ ) a very good correlation was obtained between the  $-p_A$  calculated and cohesion measured for  $W_c = 30.96\%$ .

**II Series** (Table 2, Fig. 2b). Sample was equilibrated at  $u = 1.0 \text{ kG/cm}^2 = \text{const.}$  and various  $\sigma_3$ . Pore pressure parameter  $B = \frac{\Delta u}{\Delta \sigma_3}$  was measured at  $\sigma_3 = 1.0 \text{ kG/cm}^2$ . Sample was sheared at the initial value of  $\sigma_3$  and  $u = 1.0 \text{ kG/cm}^2 = \text{const.}$  A pronounced dispersion of cohesion measurement results ( $r_{xy} = -0.77$ ), greater than in other series ( $|r_{xy}| > 0.93$ ) is probably due to a great dispersion in  $\text{tg } \beta$  determination. The angle of internal friction determined in this series was lower than in series I and decreased with the increase in water content, what could be a reason of the difference between the cohesion measured and  $-p_A$  calculated (Fig. 2b). It is also possible though, that  $W_c$  increased with the increase in pore water pressure.

**III Series** (Table 2, Fig. 2c). A good correlation of calculated  $-p_A$  and the measured cohesion was obtained for  $W_c$  about  $28\%$ , thus a value somewhat lower than that in series I. It is possible that the reason was a shorter time of aggregate storage (1 day). It is surprising though that the increased pore water pressure during the shearing did not increase this value ( $u_0 = 0.30 \text{ kG/cm}^2$  for  $W_f = 54\%$  to  $u_0 = 2.50 \text{ kG/cm}^2$  for  $W_f = 66\%$ ). In this series a very low angle of internal friction was measured ( $\text{tg } \beta = 0.021$ ), the cohesion determined may thus be overestimated and in this case the actual value of  $W_c$  may be still lower.

**IV Series** (Table 2, Fig. 2d). The comparison of the calculated  $-p_A$  with the cohesion  $c$  measured indicates two groups of points: 1)  $W_f = 55\%$  to  $60\%$ , which gave a good correlation of the values mentioned above for  $W_c = 30.96\%$  and 2)  $W_f = 46\%$  to  $50\%$  which gave a good correlation of  $c$  and  $-p_A$  for  $W_c = 24.38\%$ . Here it seems logical, that samples of lower water content indicated a lower  $W_c$ , whereas samples of higher water content indicate a higher  $W_c$  value

(Fig. 2d). Differences in sample preparation method and shearing method and high dispersion of measurement results ( $r_{xy} = -0.699$ ) make difficult the interpretation of this series.

**V Series.** It was described in the paper of Paszyc-Stępkowska [7]. Measurements were performed as in series I. A good correlation of  $-p_A$  calculation results and  $c$  measurement results was here obtained for  $W_c = 24.38\%$ . The reason of the difference in  $W_c$  value in this series and in series I may be the difference in sorption properties of the Z.M. bentonite batch used in this series (hygroscopic water content  $W_a(0.95) = 26.6\%$  [6]).

Besides series V differed from series I in:

1. Shorter time of aggregate storage (1 day compared to 1—2 days in series I),
2. Different water content range,
3. Different fraction of investigated samples (sieve 0.09 mm).

#### NORMALLY CONSOLIDATED SAMPLES (N. C.) AND OVER CONSOLIDATED SAMPLES (O. C.)

The bentonite—water mass was prepared of the given water content  $W_0$  about 100%. After several days of storage the samples were formed and consolidated isotropically. Stepwise applying the loads  $\sigma_c = \sigma_3 = 0.25; 0.5; 1.0; 2.0; 3.0; 4.0; 5.0$  and  $6.0 \text{ kG/cm}^2$ . At the termination of every step the pore water pressure should fall to atmospheric pressure  $u = 0$ . The consolidation was stopped at the assumed consolidation load  $\leq 5 \text{ kG/cm}^2$ . Some samples were tested as overconsolidated (O.C.). Then after the application of the greatest consolidation load ( $\sigma_3 = 5.0 \text{ kG/cm}^2$ ) this load was decreased in similar steps until the assumed consolidation pressure was achieved.

**VI Series.** The initial water content was a)  $W_0 = 85$  to  $92\%$  or b)  $101\%$ . Samples a) were sheared at  $u = 0$  const. ( $W_f = 65\%$  to  $75\%$ ), samples b)  $\sigma_3$  was increased by  $\Delta\sigma_3 = 1.0 \text{ kG/cm}^2$  and  $u$  by  $\Delta u = 1.0 \text{ kG/cm}^2$ , pore water pressure parameter  $B$  was measured. Samples were sheared at  $u = 1.0 \text{ kG/cm}^2 = \text{const}$ , regulating  $\sigma_3$  (except two samples which were sheared as the group a),  $W_f$  was  $59\%$  to  $76\%$ .

The group of samples of lower water content and  $u = 0$  (group a) indicated a good correlation of calculated  $-p_A$  and the cohesion measured if the value  $W_c = 31\%$  was assumed. This value should be increased to about  $35\%$  for the samples of higher water content and higher pore water pressure (group b). It should be mentioned that in series VIa a higher angle of internal friction was determined than in series VIb.

**VII Series** (Table 2, Fig. 2g). The relation between cohesion  $c$ ,



and water content  $W$ , was the same both for N.C. and O.C. samples. If the value  $W_c = 30.96\%$  was assumed the cohesion measured was higher than the calculated  $-p_A$ . A better estimate would be  $W_c$  up to  $35\%$ . For very high water contents ( $W_f = 75\%$  to  $80\%$ ) the cohesion measured was equal to or lower than the calculated  $-p_A$  and for  $W_f = 80\%$  the value  $W_c = 28\%$  should be assumed (Fig. 2g). It should be mentioned that in this series the angle of internal friction for  $W_f < 67\%$  was generally less than 0.1 ( $\text{tg } \beta = 0.015$  to  $0.089$  except one sample —  $0.109$ ), whereas for  $W_f > 67\%$  it was generally higher than 0.1.

VIII Series. Normally consolidated (N.C) and overconsolidated (O.C.) samples were sheared at  $\sigma_3 = \sigma_c = \text{const}$ , the pore water pressure  $u$  was measured. A similar relation was found between the cohesion  $c$ , measured and the water content  $W$ , both for N.C. and O.C. samples. For water contents  $< 70\%$  a good correlation between  $-p_A$  and  $c$  could be obtained for  $W_c$  about  $33\%$ . At higher water contents  $W_c = 28\%$  is a better estimate. Samples indicating cohesion exceeding  $-p_A$  indicated generally a low angle of internal friction.

#### CONCLUSIONS

Shear strength measurements were performed to find the best method of frictional component and cohesion component determination in the triaxial shear (the analysis of this problem is being performed). Results of the cohesion thus measured were compared with London—van der Waals dispersion interaction pressure calculated from a theoretical formula and from the water sorption test proposed. Assuming the crystal phase water content determined in sorption test (hygroscopic water content) there was obtained in most series a good correlation between the calculated  $-p_A$  and the cohesion measured. There was assumed though a varying number of vacancies (varying water density) or a varying number of intersheet water layers in the intersheet space.

Generally at shorter storage time, lower initial water content, and lower pore water pressure during shear lower  $W_c$  values were indicated. It seems that the crystal phase water content is not a constant value but it depends on the water conditions and stress distribution, especially pore water pressure.

The analysis of the regression line indicates, that the intercepts of  $\lg c$  at  $W_f = 0$  ranged between 2,03 (series II) and 3,81 (series VII; excluding the series IV) and that they depend on the slope of the regression line (coefficient  $a$  of the  $W_f$  term) which ranged between 0,031 and 0,058.

The coefficient of the linear correlation  $-r_{xy}$  was higher than 0,93 except the series II (0,77) and the series IV (0,70).

The angle of internal friction was the smallest in the series III ( $\text{tg } \beta = 0,02$ ), in the series II, VIb ( $u = 1,0$ ) and in series VIII ( $\text{tg } \beta = 0,06$ ). In the remaining series  $\text{tg } \beta$  was  $0,1 \pm 0,01$ .

The interpretation given above is based upon the determination of the angle of internal friction in every sample separately. The value of  $\text{tg } \beta$  ranged between 0 and 0,2. Another analysis should be based upon the assumption of an constant average value of the angle of internal friction what is a probable assumption and a generally accepted one. Samples indicating the friction angle differing from the average value indicated also a high dispersion of the cohesion determined from the regression line  $\lg c = f(W_f)$ .

Finally it should be kept in mind, that besides  $-p_A$  in cohesion there may take part also other forces, causing its increase, what was here interpreted as the increase in  $W_c^*$ .

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\* This paper and the following one (both written in March, 1974) present a step in the study of the mechanism of the shearing process. Since that time the study proceeded farther (see Proc. First Baltic Conf. on Soil Mech. and Found. Eng., Gdańsk 1975, V. 2, p. 373-386).

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**SZACOWANIE ODLEGŁOŚCI POMIĘDZY CZĄSTKAMI I ODDZIAŁYWAŃ  
DALEKIEGO ZASIĘGU W NASYCONYCH ILASTYCH GRUNTACH  
MONOMINERALNYCH**

**Streszczenie**

Przedstawiono wyniki badań trójosiowego ściskania nasyconych gruntów ilastych. Wyniki wyznaczonej w tych badaniach spójności porównano z ciśnieniem oddziaływania dyspersyjnego Londona-van der Waalsa oszacowanym na podstawie zaproponowanego testu sorpcyjnego. Przyjmując zawartość wody związanej z fazą krystaliczną oznaczoną na podstawie testu sorpcyjnego uzyskano dobrą zgodność wyników z przewidywaniem.

Autorzy przypuszczają, że zawartość wody związanej z fazą krystaliczną nie jest wielkością stałą, lecz zależy od warunków wodnych i rozkładu obciążeń, szczególnie od ciśnienia wody w porach.

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**ОЦЕНКА РАССТОЯНИЯ МЕЖДУ ЧАСТИЦАМИ И ВОЗДЕЙСТВИЯМИ  
ДАЛЕКОГО ЗАХВАТА В НАСЫЩЕННЫХ ИЛИСТЫХ МОНОМИНЕРАЛЬНЫХ  
ПОЧВОГРУНТАХ**

**Резюме**

Рассматриваются результаты исследований трехосевого сжатия насыщенных илистых почвогрунтов. Результаты определенной в этих исследованиях связности сравнивали с давлением дисперсного воздействия Лондона — ван дер Ваальса, оценным на основании предложенного сорбционного теста. При принятии содержания воды связанной с кристаллической фазой, определенной на основании сорбционного теста, было получено хорошее сходство результатов с предположенными.

По мнению авторов содержание воды связанной с кристаллической фазой не является постоянной величиной; оно обусловлено водным режимом и распределением нагрузок, а особенно давлением воды в порах.