Physics of the Shearing Process of Saturated Clays

Physique du Cisaillement des Argiles Saturées

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SYNOPSIS. Physical reasons of some mechanical phenomena are proposed for Z.M.bentonite and for some natural claye. Attractive /p_A/ and repulsive /p_R/ long-range particle interaction pressures are calculated and compared with the measured stress values. At high w.c. /$W > W_p$, $p_R \gg -p_A$, dispersed system/: when u=0, $\frac{1}{2}\sigma'_c \cong p_R$; when $\sigma'_3=0$, $p_R \cong -u$ and $\frac{1}{2}/\sigma'_1-\sigma'_3/_f \cong p_R$. At low w.c. /$W < W_p$, $-p_A > p_R$, flocculated system/ interparticle contacts unevitably develop and they carry pert of applied pressure: when u=0, $\frac{1}{2}\sigma'_c > p_R$; when $\sigma'_3=0$, $p_R > -u$ and $\frac{1}{2}/\sigma'_1-\sigma'_3/_f \cong -p_A$. The condition of $-p_A = p_R$ is fullfilled at w.c. about W_p/here σ'_c was about 1kp/cm^2 and half the interparticle distance d=35Å/. During consolidation and/or shearing process average particle thickness may vary as the function of stress applied.

INTRODUCTION. The interaction through a thin /rigid/ layer of water is usually assumed to be the cause of true cohesion. Here this water layer is supposed to be of pronounced thickness /2d=50Å to 100Å,diffuse layer,non-rigid/ and the long-range interactions /attractive, p_A, and repulsive, p_R/ are assumed as the reason of the shear strength.

In previous study of this author the comparison of estimated long-range interactions, p_R and p_A, with the measured shear strength indicated that either both of them or only one of them may be the cause of clay strength. This problem needed a more detailed research and explanation.

The diffuse layer repulsion pressure, p_R, was considered in detail by BOLT and MILLER /1955/ and BOLT /1956/. A thorough study of London-van der Walls interaction pressure, p_A, was performed /STĘPKOWSKA, 1970, 1975b/. The water sorption test /WST/ was elaborated, permitting the determination of crystal phase water /W_h/p/p$_o$=0.95; 200°C//, of the external specific surface, $\bar{S}$, and of other properties /estimation of CEC, montmorillonite, M, and kaolinite, Kl, content indexes, particle thickness, δ/. The eventual interaggregate water, W_{mac}, may also be estimated and half the interparticle distance, d, may be obtained for the given w.c. /STĘPKOWSKA 1973a and b, 1975b, 1976/:

$$d = \frac{W - W_h - W_{mac}}{\bar{S}\rho} \qquad /1/$$

/here ρ =1.0g/cm^3/ is the density of free liquid water/.

The knowledge of this parameter enables the estimation of p_R end p_A for the investigated clay-water system.

Thermodynamic considerations of the mechanical processes in clays indicate that the decreased potential energy, dV<0, may be dissipated in form of heat: dQ=-dV_R in pure tension and dQ=-dV_A in pure compression /1975a,1976/.

The theoretical micromechanism of the shearing process presented herein is supported by some check experiments, performed on Z.M.bentonite and on some natural clay samples /M. Ill, partly interstratified, with possible Chl and/or Kl admixtures/. The properties of the investigated samples are presented in detail elsewhere. Some tests were performed on Sedlec kaolin but their interpretation is not complete as yet.

ELEMENTS OF CLAY MICROSTRUCTURE. Crystallite /particle/ is assumed as the smallest elementary component of clay structure. XRD study, WS Test and energetic considerations indicate the following: the crystallite of Z.M.bentonite is composed of several sheets of montmorillonite /plus probably one mica sheet/ of a thickness of 10Å each sheet. Number of sheets per particle /Nr/ varies between 5 and 8. On the external surface and in the intersheet space there are three-molecular water layers present, of the thickness of 9Å to 10Å each. The total thickness δ of a crystallite is thus ~100Å /Nr=5/ to ~160Å /Nr=8/. The external specific surface, $\overline{S}$, varies between ~160m^2/g /Nr=5/ and ~100m^2/g /Nr=8/.

In certain natural clay /H.K./ containing little or no quartz, δ measured by XRD and WS Test was 200Å to 350Å and the corresponding values of $\overline{S}$ were 65 to 25m^2/g. In clays from some other localities the particle thickness δ measured was 150Å to 300Å /D.clay/, 200Å to 220Å /Bydgoszcz clay/, 700Å to 800Å /B.clay, from WST/.

Clay crystallites are arranged parallel to each other /due to diffuse layer repulsion, p_R/, forming domains or tactoids. The mutual distance depends on w.c. and it may vary /Z. M.bentonite/ between ~140Å at liquid limit and ~70Å at plastic limit, W_p, around which value the repulsion equals attraction. In the case of absence of interparticle links and of presence of bivalent exchangeable cations / δ=100Å to 140Å/:

at $W=W_p$ and d=70Å, $p_R = -p_A$ /2/

Below this w.c. /attraction exceeding repulsion/ interparticle bonds develop either due to ionic lattice attraction between sheets curled at the crystallite edges /montmorillonite/ or due to crystallite reorientation and edge-to-face contacts probable in kaolinite. These bonds impede further decrease in interparticle distance /with load increase/ as the bending strength of crystallites is much higher than p_R. Unbending of crystallites after unloading may influence the suction measured /u < 0/.

Domains /tactoids/ in random mutual orientation form aggregates /peds/, of the size which is measured as grain size. In natural clays interaggregate water, W_{mac}, may occur, in Z. M.bentonite /N.C./ EM-study and calculation result indicate that W_{mac}=0.

For a group of preconsolidated natural clay samples from a given locality this value can be estimated from WS Test, i.e. from the intercept of the regression line /transformed Eq. 1/:

$$W - W_h = W_{mac} + d_{av}\overline{S} \qquad /3/$$

In highly O.C. clay /e.g. due to glacier/,d may be assumed as close to an average value, d_{av}. The regression line calculated for 11 samples of B.clay /mainly from the depth exceeding 20 m/ was:

$$W_f - W_h = 4.64 + 0.285\ \overline{S}/\%/ \quad r_{xy}=0.9795 \qquad /3a/$$

indicating W_{mac} = 4.64% and d_{av} = 28.5Å.

MICROMECHANISM OF THE SHEARING PROCESS. Isotropic consolidation of Z.M.bentonite from w.c. near to the liquid limit $W_o \approx 100\%/\sigma_o$=0.25 to 5.0kp/$cm^2$/ was performed in Norwegian type triaxial test equipment. Samples were sheared after unloading to σ_3=0 with pore water pressure, u, measurement /Plexi null device/ at a constant strain rate of 1.6 mm/hour.

The lines in Fig. 1 represent the calculated values of p_R and p_A for concentration range of 10^{-3} to 10^{-4}n and particle thickness range, δ=100Å to 140Å /most probable values in investigated bentonite/. The values of p_R are approximately valid also for natural clays; usually their δ and $-p_A$ values are higher.

I."Dispersed" structure: $p_R > -p_A$, $W>W_p$, d>35Å $\sigma_c \leqslant$ 1kp/cm^2. If the initial w.c. is high enough, σ_c is carried mainly by p_R and after termination of the consolidation process /pure compression/:

N.C. /u=0/ $\frac{1}{2}\sigma_c = p_R$ /4/

The decreased potential energy of attraction is dissipated in form of heat /1975a, 1976/:

$$-dV_A = dQ_A \qquad /5/$$

After undrained unloading / $\sigma_3=0$/:

$$p_R = -u \qquad /6/$$

Experimentally measured suction values /Fig.1/ are close tothe calculated p_R values. Small differences may be due to p_A impeding reversible unloading, to unbending of interparticle links and to experimental and/or estimation error.

The shearing process may be presented here as pure compression /dd < 0/. Work is performed only when decreasing the interparticle distance

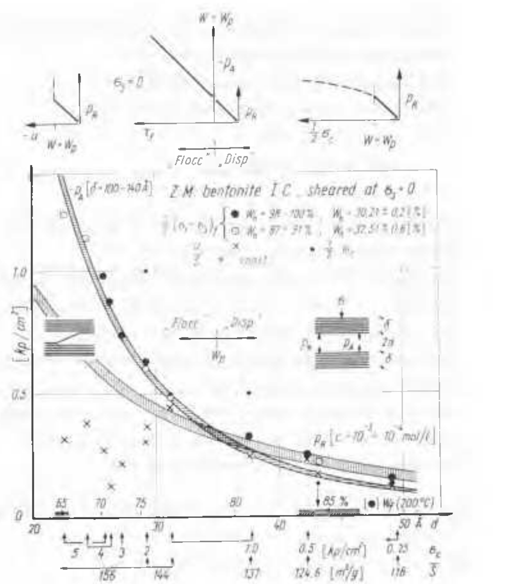

Fig 1

no work is done when the particles are displaced parallel to each other /the potential gradient in this direction equals zero/. Work of external forces:

$$dW = \sigma_d \, d \, \varepsilon_d \qquad /7/$$

causes a corresponding change in potential energy of repulsion:

$$-dV_R = p_R dd \qquad /8/$$

where $\qquad d\,\varepsilon_d = 2\,dd \neq 0 \qquad /9/$

When particle orientation is random, when /7/ equals /8/ and Equation /5/ is true, this leads to the general expression of Eg. /4/.

In unconfined compression /$\sigma_3=0$/:

$$\tfrac{1}{2}/\sigma_1 - \sigma_3/_f = \tfrac{1}{2}/\sigma_1/_f = p_R \qquad /10/$$

This was measured in Z.M.bentonite /Fig.1/ at $\sigma_c < 1.0 kp/cm^2$. Sheared samples failed mainly by bulging.

Remoulded Na-bentonite and /Na+Ca/-bentonite, indicating high p_R values, behaved in quick triaxial compression in accordance with the above presentation /Fig. 2/.

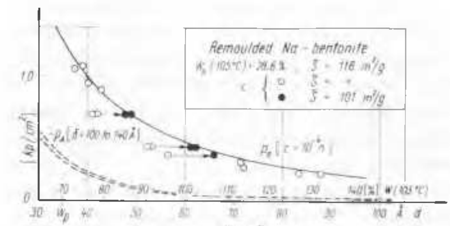

Fig 2

II."Flocculated" structure: $-p_A > p_R$, $W < W_p$, $d < 35Å$, $\sigma_c > 2 kp/cm$. Here a part of the consolidation pressure is carried by the soil skeleton and only the rest of it is carried by p_R.

Thus at N.C./u=0/ $\frac{1}{2}\sigma_c \gg p_R \qquad /11/$

On unloading in undrained condition:

$$\sigma_3=0 \qquad -u \leqslant p_R \qquad /12/$$

The swelling of the sample in drained condition is limited both by the attractive pressu-

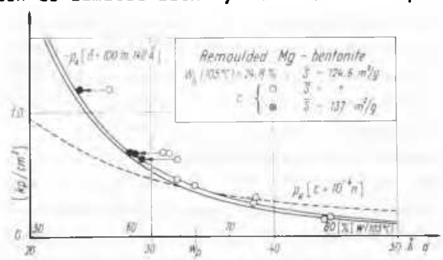

Fig 3

re p_A /exceeding repulsion p_R/ and by the interparticle links. Final w.c. cannot exceed W_p and in O.C.bentonite /Z.M./ it actually did not.

The shearing process in this w.c. range may be considered as pure tension /dd>0/ in analogy to the compression process.

Heat dissipating in this process is partly due to a decrease in potential energy of repulsion

$$-dV_R = dQ_R \qquad /13/$$

and partly due to crystallite deformation. Work of external forcos /7/ causes change in the potential energy of attraction:

$$-dV_A = p_A \; dd \qquad /14/$$

Assuming /7/=/14/ and /9/

$$\frac{1}{2}/\sigma_1 - \sigma_3/_f = -p_A \qquad /15/$$

This was approximately observed in Z.M.bentonite samples in unconfined compression /σ_3=0/, see Fig.1, and in triaxial compression of N.C. and O.C. samples /results will be presented elsewhere/. At failure the sheared samples mostly indicated a distinct shear plane.

Remoulded Mg-, Ca-, Fe-, Al, and H- bentonites behaved in accordance with this presentation /see Fig. 3/.

Perfect correlation between the theoretically calculated forces and the measured shear strength was obtained, assuming a stepwise increase in external specific surface, $\overline{S}$, /decrease in Nr/ with the increase in σ_c and/or shear etrength. Though the ionic lattice attraction has a very high component perpendicular to the sheet face, its component parallel to the sheet face is zero and creep phenomenon is probable. The values of Nr and $\overline{S}$ assumed in calculation were equal to values determined by XRD /particle thickness/ for samples oriented from a slurry and for powder samples /WS Test gave a good check/. The values assumed were:

σ_c < 1kp/cm^2	Nr=6.5 or 7	$\overline{S}$=124.6 or 118m^2/g
=1kp/cm^2	=5.5 or 6	=144 or 137 m^2/g
=2kp/cm^2	=5 or 5.5	=156 or 144 m^2/g
> 2kp/cm^2	=5	=156 m^2/g

A unique relation was obtained between the shear strength and the interparticle distance 2d for all the investigated Z.M.bentonite samples /N.C.,O.C., remoulded and statically compacted/. Similar results were obtained for a series of stiff H.K. clay samples, preconsolidated by a glacier /1975b/. Interparticle distance was estimated by WS Test. The average value of calculated therefrom $-p_A$ was 0.74 kp/cm^2. The average value of shear strength measured was 0.71kp/cm^2.

The following regression lines for H.K.clay samples were calculated:

$$1/\ \frac{1}{2}/\sigma_1 - \sigma_3/_f = -0.0522\ d_f + 2.411 \quad /kp/cm^2/ \qquad r_{xy} = -0.5781 \qquad /16/$$

$$2/\ \frac{1}{2}/\sigma_1 - \sigma_3/_f = 1.043\ [-p_A/\delta = 300Å/] + 0.004 \quad /kp/cm^2/ \qquad r_{xy} = 0.7980 \qquad /17/$$

Numerical value of correlation coefficient of Eq./17/, as compared to that of Eq./16/, indicates that p_A is responsible for the shear strength.

B.clay from the depth of 2 to 11.5m, sheared at σ_3=1 to 2kp/cm^2, indicated shear strength of 1.52 to 2.10kp/cm^2, whereas the average estimated theoretical value was $-p_A$=1.54kp/cm^2 /δ=700Å, d=28.5Å, see Eq. 3a/.

CONCLUSIONS. In saturated swelling /montmorlilonitic/ clays, indicating no cementation and no non-clay mineral admixtures:

1. The reason of the shear strength is:
   a. London-van der Waals attraction p_A if $-p_A > p_R$ and $W < W_p$
   b. diffuse layer repulsion p_R if $p_R > -p_A$ and $W > W_p$
2. Plastic limit, W_p, is close to w.c. where attraction equals repulsion.
3. Increase in stress applied may cause a decrease in average particle thickness and an increase in average shear strength /shear plane passing through crystallite parallel to its surface/.

These conclusions were drawn for Z.M.bentonite and Polish natural clays and they should be checked for other types of soils.

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