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shows very early understanding of importance  
and special nature of thin water layers on clay minerals

(but '41 paper ideas seem new at time)

## NEW FACTS ABOUT SURFACE-FRICTION.

BY CH. TERZAGHI.

### SYNOPSIS.

*Friction between Smooth Surfaces: Physical Properties of Clays.*—In the present paper the author discusses a number of preliminary experiments leading to an investigation of the physical properties of clays. Since plastic deformations of clay-bodies involve the sliding of the smooth clay particles upon each other, in order to determine the character and the laws governing the frictional forces, the author studies the behavior of smooth glass plates placed in contact under different conditions of loading. As a result of these experiments it is established that the frictional resistance between two surfaces is not due to the shearing strength of a cushion of air or water; but to the existence of microscopic particles that deposit themselves on the rubbing surfaces. Frictional resistance was found to be independent of the thickness of the air cushion.

*Properties of Very Thin Layers of Water; Permeability and Water Contents of Clays.*—A drop of water was placed between two glass plates and was allowed to evaporate. When the thickness of the layer of water was reduced to about  $100 \mu\mu$ , the evaporation stopped completely, suggesting that the molecules of a solid are able to exert forces over distances of the order of  $50 \mu\mu$ . Such thin layers of water have, beside viscosity, shearing and tensile strength. The author uses this result to explain the facts: (1) that layers of clay are impermeable unless the head exceeds a certain minimum; (2) that the water contents of clays do not drop below a certain limit; (3) that a drop of water does not spread over a surface wetted by water.

*Theory of Surface Friction.*—As a result of the observations mentioned and of a new set of experiments, the author concludes that the ordinary laws of friction of rest apply only where contact between the rubbing surfaces must be enforced by outside pressure. When two even surfaces are in contact the explanation of the causes of friction is not so simple on account of the presence of small particles on the surfaces.

$$\begin{aligned} 10^{-12} \text{ m} \\ 10^{-9} \text{ mm} \\ (1 \text{ \AA} = 10^{-10} \text{ m} \\ = 100 \mu\mu) \end{aligned}$$

THE following article may be considered as a preliminary report on a series of investigations carried out by the author in the Laboratories of Robert College, Constantinople (Branch institution of N. Y. State University).

### I. INTRODUCTION.

Most of the properties of clays, as well as the physical causes of those few properties that have been investigated, are unknown. We know nothing about the elasticity of clays, or the conditions that determine their water capacity, or the relations between their water content and their viscosity, or the earth pressure that they exert and not even about the physical causes of the swelling of wetted clays. As a consequence

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in two different ways; Either the surface of the edge of the waterspot is covered by a layer of saturated vapor that is kept from diffusion by molecular attraction through the molecules of the solid body, or the water-molecules are kept in their position by the same forces. But if the molecules of the solid body are able to act over a distance of more than  $50 \mu\mu$  on the rapidly travelling molecules of saturated vapor, the more they will exercise their solidifying influence on the quieter molecules of water within the same range of distance. The distance of  $50 \mu\mu$  is identical with the distance (measured by Quincke)<sup>1</sup> up to which glass is able to influence the angle of contact between water and silver.

Combining the result of experiment No. 6 with the fact (observed by Seelheim and discussed by Forchheimer)<sup>2</sup> that layers of clay are impermeable unless the head exceeds a certain minimum, which is a function of the thickness of the layer, we are now obliged to attribute to the surface layer both the qualities of a solid and of a liquid, at least in the case where such surfaces meet each other between the surfaces of two solid bodies. This involves within the film of the liquid not only viscosity but shearing- and tensile-strength too.

The double thickness  $0.1 \mu$  of the contact-layer is the approximate width of voids in a thickly packed mass of grains whose size is smaller than  $1$  or  $2 \mu$ . According to Atterberg<sup>3</sup> no powder with uniform size of grains shows plasticity unless its particles are smaller than  $2 \mu$ .

Experiment No. 6 explains the fact, observed by the author, that the water content of a clay exposed to the air at ordinary temperature does not drop below a certain limit ranging between 4 and 8 per cent. of the weight of the dry matter (the exact value depending on the size and particularly on the shape of the grains).

The fact that the influence of the molecules of the solid body is exerted up to a distance of more than  $50 \mu\mu$  from the surface seems to bear a relation with the unexplained fact, that a drop of water does not spread over a surface wetted by the water, but that its surface slopes down to the surface on which it rests, forming with it a certain angle of contact. If the influence of the molecules of the solid body were limited to a distance equal to the thickness of the surface layer of the liquid ( $0.06 \mu\mu$ ), the mentioned effect would not be possible as a simple statical consideration shows. The author explains the phenomenon as follows: The surface layer of the waterdrop is not anchored to the surface  $AB$  of the glass-sheet (Fig. 1) but to the semi-solid surface layer  $ABCD$  and is therefore unable to spread because the area of this layer is limited. Another

<sup>1</sup> Annales de Chimie et de Physique.

<sup>2</sup> Ztsch. d. Ver. d. Ing., 1901.

<sup>3</sup> International reports on pedology, 1913.

$10^{-4}$  mm

simple experiment made with an eye-glass and a wet handkerchief indicated too the semi-solid character of thin films of water. Sweeping the handkerchief over the glass, the glass surface was covered with a thin film of liquid showing interference-colors. The surface of drops of water placed upon this film formed with it an angle of contact just as

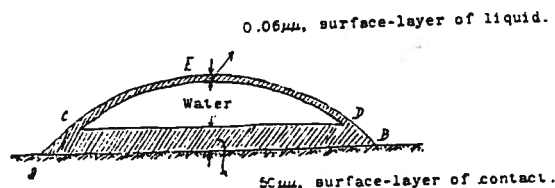


Fig. 1.

they would do it they were immediately placed on the glass surface, they showed no tendency to spread and their behavior was not at all influenced by the gradual evaporation of the film that surrounded them. While the film itself did not contract to drops as a thicker film would do but it retained its original relief until it evaporated.

### III. ELASTIC THEORY OF SURFACE-FRICTION OF REST.

Under the influence of the results of his observations the author assumes that surface-friction stands in direct proportion to the area of those parts of their surfaces which are closer to each other than  $0.1 \mu$  (called area of contact) and distinguishes three different cases of friction:

*Case (a). Very Smooth and Even Surface, Low Surface-Pressure.*—The action is transmitted by intermediate bodies of microscopical size (Fig. 2, a). The area of surface of contact is, according to the formulas

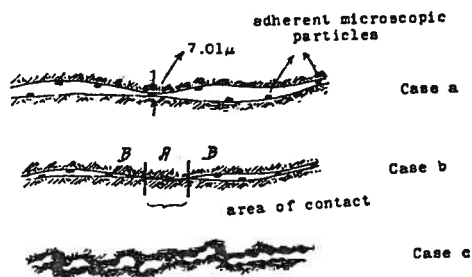


Fig. 2.

of Hertz, smaller the smaller the radius of curvature at the place of contact. Hence, as the shape of the intermediate bodies is a matter of chance, the coefficient of friction is extremely variable.

*Case (b) Very Smooth and Even Surfaces, High Surface Pressure (Fig. 2, b).*—The intermediate bodies disappear in depressions produced above and underneath them by high local pressure. The surfaces of the two main-bodies come in contact, the radius of curvature of this surface is by far bigger than the radius of curvature of the surfaces of the microscopical bodies, and the coefficient of friction goes rapidly up. With increasing pressure the peripheral parts *BB* of the surfaces whose radius of curvature is still greater than that of the central part *A* come in contact, the coefficient of friction increases therefore furthermore, although not as rapidly as at the limit between case (*a*) and case (*b*). These assumptions are verified by a series of facts published 1829 by Rennie.<sup>1</sup> This author found for the coefficient of friction *f* between steel and iron at different surface-pressures the following values:

Pressure  $p = 8.79 \text{ kg. cm.}^{-2}$ ,  $f = 0.166$  corresponding to a later stage of case (*a*).

$p = 23.62 \text{ kg. cm.}^{-2}$ ,  $f = 0.333$ , earlier stage of case (*b*).

With further increasing pressure  $p$  he found an increasing  $f$  until he obtained for  $p = 47.25 \text{ kg. cm.}^{-2}$ ,  $f = 0.403$ .

Experiments carried out with other materials led him to similar results indicating that the coefficient of friction rises first rapidly and then slowly with increasing pressure.

*Case (c). Bodies with Rough Surfaces.*—The friction is a complicated result of the effect of molecular attraction due to contact and of the fact that the asperities of the two surfaces stand to each other in a similar relation as the teeth of two gears (Fig. 2, *c*). But as the surface of contact is already at the very beginning more considerable than in case (*a*), as it can never reach as big values as in case (*b*) and as furthermore the second element which determines the frictional resistance in case (*c*), the geometrical form of the two surfaces, is practically independent of the pressure, the coefficient of friction is a fairly definite figure and this explains the curious fact that the complicated causes of friction between rough bodies lead to a simpler effect than the seemingly simple causes of friction between two smooth surfaces.

The indicated theory removes the apparent contradiction between the fact of tangential frictional force and the molecular theory of matter. As long as the surfaces are in contact they adhere to each other not only in tangential direction but in every other direction too. But the adhesion perpendicular to the surface cannot be observed because as soon as the pressure is relieved the area of contact becomes again nearly zero, the surface resuming their original shape and this remark leads to a very

<sup>1</sup> Phil. Trans., 1829.

important conclusion essential for the understanding of the properties of clays:

*The ordinary laws of friction of rest are only applicable to the friction between bodies whose original surfaces do not fit each other and whose contact must be enforced by external pressure. Two bodies joining each other with perfectly even surfaces would present not only a lateral resistance against displacement but resistance against separation too.*

The latter fact has been demonstrated by the following striking experiment: A very dilute solution of a clay, distinguished by the flat shape of its particles and very strong Brownian movements was placed on a thin sheet of glass, inside a ring of a height of 2 mm. Five minutes after having filled the ring, the cylindrical space was covered with a glass cover, so that there was no trace of air between the bottom and the cover, and the whole was turned upside down. Twelve hours later the vessel was turned again, and after another twelve hours top and bottom were examined under the microscope. All particles smaller than  $\mu$  adhered to the glass cover and all particles bigger than this size stuck to the bottom. The colloidal particles showed no trace of Brownian movement, apparently kept in their position by molecular forces. Turning the vessel upside down again the coarse particles remained in their places on the upper surface of the water-body. A drawing was made of some characteristic parts of the crystal groups and twelve hours later it could be stated that no grain had left the top-cover, a clear proof, that in the case of contact without external pressure the retaining forces act not only in a horizontal but also in vertical direction.

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