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1. ON THE MOLECULAR STRUCTURE OF WATER AND ITS PROPERTIES REGARDING CAPILLARY PHENOMENA

As a rule substances which are liquid at normal temperature show molecules as greatest independent structure units. This is especially applicable to water, the surface- and capillary phenomena of which will be taken into consideration, concerning their significance in soil mechanics, whereby their binding effect will be regarded especially.

It is true that combinations of space lattice structure which hold a tetrahedral arrangement were found in water, but they are of very little extension only, develop locally and temporarily and break up again; their determination and effect are, in the main, limited to roentgenographic phenomena.

Binding forces of molecules cause an internal pressure of water the value of which, calculated from the equation of van der Waals, amounts to about 11.000 kg/cm² at a temperature of 0° Celsius and atmospheric pressure. As the statistic average value per square unit it is also to be denominated cohesion, because it represents a special form of this property.

Such a kind of denomination is in the sense of the physical point of view, but it is contradictory to the frequent practice in soil mechanics also to call shearing-resistance cohesion. The high value of internal pressure of water has to be attributed to the fact that the molecules are closely packed because of the minute sphere of action of van der Waals' forces which are known to be inversely proportional to the 6th power of the distance of molecules.

Besides binding forces there are also repulsive forces which are according to van der Waals' equation influenced thermodynamically to a large extent. Permutability of molecules and thereby the small internal friction (shearing-resistance) of water is to be derived from the thermodynamical movement of molecules. Above mentioned rudiments of a space lattice structure are not able to disturb the isotropy of water regarding internal friction.

The fact that the surface of a liquid always has to be perpendicular to the resulting force on the occasional spot results from the movability of molecules. From this furthermore follows that tensions in a liquid and density have to be isotropic. Variations from both these properties may be found within the sphere of action of water-molecules itself or in that of coating solids only.

Opinions concerning the radius of the sphere of action of water-molecules diverge. As far as there is a sharp limitation at all, there are many reasons for the presumption that it is limited essentially to the distance of neighbouring molecules so that the radius of molecular action is of an order of magnitude which corresponds to the molecular diameter.

A film of water which is adsorbed by solid substances loses the properties bound to mobility of molecules. In this form of soil-water van der Waals' forces are surmounted by the multiple stronger and further reaching superficial binding forces of the solid phase in the case of wetting; the thickness of the film is valued approximately from 2 to 400.

In this film water assumes properties which are similar to those of solids; primarily it acquires shearing-resistance to a certain extent and thereby stability of form, perhaps because of diagonal action of further reaching adsorbing forces. Consolidation of water increases in the adsorbed layer towards the surface of the solid substance.

Films adsorbed by soil-granules may unite; thus water gains binding force and thereby becomes an important cause for true cohesion of soil.

The following considerations leave adsorbed films unregarded and remain limited to surface- and capillary phenomena as well as to the thereby caused untrue cohesion of soil.

2. PRINCIPAL FACTS ON SURFACE- AND CAPILLARY PHENOMENA.

If the surface of a liquid is plane, forces arise perpendicular to it which according to Laplace's theory pull the molecules into the interior and thereby cause the surface pressure. Its value is equal to the internal pressure. But attractive forces between the molecules correspond, in an equilibrium state, to equal repulsive forces on the surface as well as in the interior of a liquid, so that, because of static considerations, there is no reason to speak of so called unbalanced attractive forces in the surface when the surface is plane.

If the surface of a liquid shows a curvature, the cause of which is not decisive, the surface-pressure undergoes an alteration which is dominated by the known law:

$$\Delta k = \pm \alpha \cdot \kappa$$

The additional surface-pressure Δk , a tension in the sense of the theory of elasticity of the dimension dynes/cm² or kg/cm² is proportional to the average curvature κ ; the surface-tension α appears in this respect as factor of proportionality of the dimension dynes/cm or kg/cm. The total pressure perpendicular to the surface amounts to :

$$p = k + \Delta k = k \pm \alpha \cdot \kappa$$

In case of an unvariable average curvature of a surface the direction of surface-pressure is strictly perpendicular to the surface but it diverges if this condition does not exist.

In case of a convex surface the additional surface-pressure Δk is directed towards the interior of the liquid; compared to the plane surface, thus, an excess of surface-pressure i.e. a radial surpressure is resulted.

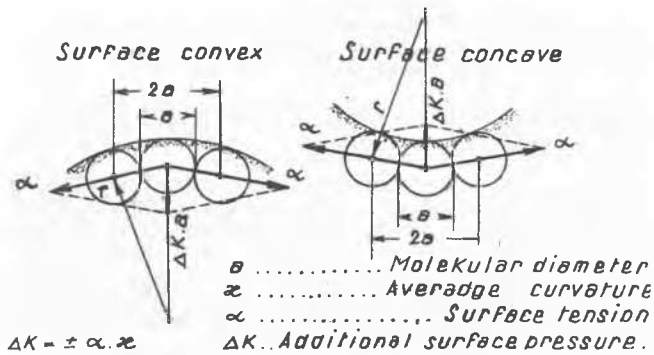
In case of a concave surface of a liquid Δk acts into the exterior and thereby cause a diminution of the surface-pressure i.e. a radial underpressure. It would not be necessary to quote this if not a contradictory point of view was supported by some other authors.

The explanation for the additional surface-pressure usual to be met with is according to Laplace's theory proceeding from a radius of molecular attraction of the order of magnitude $\delta = 10^{-6}$ cm. Whilst this sphere of action for a molecule lying in a plane surface is hemispherical, a meniscuslike shaped altered form and thereby a different surface-pressure is caused by a curved surface. But this kind of

interpretation does not lead to an explanation of surface-pressure, free from objection.

In reality the causes for surface-pressure have not become clear yet. Possibly it is connected with directed arrangement of molecules in the surface which are permanent dipolar in many liquids, especially in water.

Since pressure in a liquid must result from predomination of attractive molecular forces in opposition to repulsive ones the radial surpressure in a convex surface of a liquid may be explained by the direct effect of an additional, radially headed molecular attraction; but also additional arising tangential attractive forces in the surface of a liquid may secondarily cause the same phenomenon (Fig. 1.). If the surface is curved concavely either a radial repulsion which surmounts the attraction may be the cause for the diminuation of the pressure or additional attractive forces in tangential direction, respectively, may, as before, be considered as primary cause.



Relation of superficial molecular
Forces to Surface-Pressure.

FIG. 1

3. ON PRESENT OPINIONS ABOUT SURFACE- AND CAPILLARY PHENOMENA

The movability of molecules brings about that the surface-pressure in liquids becomes evident in a manner as it can not arise similarly in gases and solids, and is avoided in the first case by thermodynamical molecular movement, and by shearing-resistance in the second.

But surface- and capillary phenomena do not offer a possibility to measure the surface-pressure k and thereby the surface-pressure in a curved surface Δk discovers itself in many phenomena which therefore may be used for the measuring of its value. There the surface-tension α , more suitably called capillary-constant, always arises as material constant.

From the fact proved by Plateau's experiment that liquids always assume a spherical shape if external influences, especially gravity, are eliminated, no matter how great the volume is, and from similar facts, the conclusion was drawn that liquids of a given volume strive for a shape with smallest possible surface. From this again the presence of tangential surface-tension was concluded.

There are different opinions about surface tension. It is used as true force for the explanation of surface- and capillary phenomena on the one hand, but it is disputed any reality, and only conceded formal existence on the other. The difference of opinions is of no importance for many physical phenomena; but it influences the explanation of capillary pressure of soil, as the following examinations will show.

It be anticipated that the following exhibitions base upon the opinion of physicists who regard superficial pressure as formal conception only.

4. EXPLANATION OF SURFACE- AND CAPILLARY PHENOMENA WITHOUT HAVING RECOURSE TO THE CONCEPTION OF SURFACE-TENSION.

If the surface of a liquid is spherical as it is the case in the formation of drops, or if it is so extended that the marginal effect of other substances may be slighted as with surface-waves (ripples), the surface-pressure is transmitted directly to the liquid itself, There is no reason to suppose the existence of surface-tension at such phenomena. If the liquid is exposed to the molecular action of other substances at the same time the capillary phenomena are usually indicated by the presence of margins in the liquid-surface. At such margins it is not believed to be possible to renounce the introduction of surface-tension.

To explain, for instance, the rise of a wetting liquid in a vertical capillary tube it is assumed that this phenomenon is caused by the surface-tension acting vertically upwards in the periphery of the tube section. As reaction to the surface-tension the capillary tube is said to be exposed to pressure in axial direction. Therewith the transmission of forces between the meniscus and the capillary tube might only be performed by the minute adhesion onto the tube-wall or by the even smaller internal friction of the liquid, respectively.

But the capillary rise of a wetting liquid can be explained without taking recourse to fictive surface-tension as well. The molecular attractive forces between the tube-wall and the wetting liquid which are presumed to be acting perpendicular to the interface cause a concave meniscus.

In its curved surface arises a diminished surface-pressure. Under the supposition of a spherical shape the radial directed underpressure is equally distributed. The resulting underpressure acts upwards, and regarding its value it is equal to the rising force which is calculated by means of the surface-tension.

The underpressure in the meniscus which acts in the molecular surface-layer may be balanced in two ways.

a) The surface of a liquid may be exposed to tension like a membrane and transmit the underpressure to the wall of the tube, according to the generally supported opinion. It was pointed out before that always a surplus of tangential molecular attractive forces had to arise in a curved surface as far as those may be regarded as a primary cause for surface- and capillary phenomena; because of the same considerations such a membrane had to be exposed to pressure no matter whether the surface is convex or concave.

But out of this the conclusion were to be drawn that the walls of the capillary tube are exposed to traction, and that just the contrary of that effect exists which is said to cause the capillary pressure in coherent soil.

b) Since, according to this, an effect of a membrane in the liquid surface leads to conflicting conclusions, there is no other way than to presume that the underpressure arising in the concave meniscus is submitted directly to the liquid without tangential effect. Thereby the liquid is risen, and, so to speak, is suspended by the meniscus. No strain of the capillary tube can arise there.

In a non-wetting liquid a convex meniscus is formed because of the comparatively small

value of molecular attraction of the glass-walls. In its surface there is a surpressure directed towards the interior of the liquid which ought to create tractive tensions in the walls of the capillary tube according to present presumptions. It is not difficult to recognise, contradictory to this interpretation that the surpressure, transmitted directly to the liquid, exhausts itself by creating a difference of pressure between the free plane surface and the capillary meniscus of the liquid.

5. SOME MORE EXAMPLES FOR THE EXPLANATION OF SURFACE- AND CAPILLARY PHENOMENA WITHOUT TAKING RECOURSE TO SURFACE-TENSION.

Before discussing the reaction of the described presumption upon the interpretation of capillary pressure, customary in soil mechanics, some more examples for the interpretation of surface- and capillary phenomena may be quoted without referring to surface-tension.

The interpretation of surface-phenomena in the soap-bubble offers a good insight. There is a surpressure in the outer surface because of its convex shape, and an underpressure in its concave interior surface. Both effects together cause the pressure to which the enclosed air is exposed.

If the presence of surface-tension were presumed in both surfaces tangential pressure would arise, and the necessity of compression of the included air would not exist. But since it is proved that there is a higher atmospheric pressure in the interior of the soap-bubble it has to be concluded that the total, additional surface-pressure in radial direction, thus composed by two parts of almost the same value, immediately is counter-balanced by the pressure of the included air. Also if there is no possibility for compression since the air is able to escape no tangential forces arise but the bubble shrinks.

For the same reason drops of liquid are totally exposed to the increased internal pressure caused by the convex curvature of their surface.

Cavities in the interior of a liquid are surrounded by a layer of superficial molecular underpressure. If such cavities are filled with air the underpressure is balanced by compression of the contents. In a similar manner soil-particles suspended in water are exposed to a pressure corresponding to the curvature of their surface which compensates the underpressure acting in the interface on the side of the water. Finally the cavitation bubbles may be pointed out which are found on screw-propellers and on turbine-blades where the underpressure caused by the concave curvature of the surface contributes towards their extremely quick collapse; but the collapse of the bubbles may finally be derived from the molecular attractive forces between the surface of the propellers or wheels and the water, because otherwise no explanation for the extremely strong forces can be found.

6. THE REACTION OF CAPILLARY WATER IN COHERENT SOIL.

Henceforth an explanation of capillary phenomena in coherent soil is given employing the detailed resumptions.

If a part of soil is of limited dimensions only, and if evaporation can act on all sides menisci are formed round about in the pores between the soil-granules. The underpres-

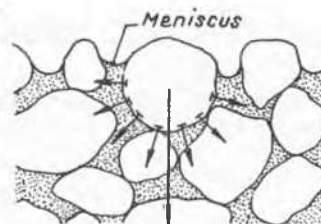
sure in their concave surfaces can not be compensated by capillary rise of water. Therefore all the capillary water contained in the pores is exposed to a corresponding underpressure. Variations of underpressures caused by the changing diameter of pores are therewith compensated by little flow of porewater and the interchanging of soil-granules connected with this.

A drop of liquid with two menisci contained in a capillary tube represents a physical object, comparable to this phenomenon.

In a part of soil of great dimensions which is drying out on its surface also menisci will appear when the evaporation on the surface continues. But since no capillary rise is available and since also a compensation of pressure is not possible as it is the case in a limited part of soil, an unbalanced static underpressure continues to exist. It causes a pore-flow in the soil towards the surface and the further reaction of the soil depends on the water supply's being able to cover the superficial loss of water by evaporation, at a gradient resulted by the capillary underpressure. If this is not the case shrinking phenomena of soil appear when desiccation continues.

7. EXPLANATION OF UNTRUE COHESION AND SHRINKING PHENOMENA IN COHERENT SOIL.

The causative connection between shrinking phenomena in clay-soil and capillarity is so apparant that no other explanation need be considered. But since no pressure is transmitted from the menisci of capillary water to the solid phase capillary pressure has to arise some other way. The explanation for it can be found in Fig. 2. which represents an enlarged transverse section through the surface of coherent soil.



Enlarged Transverse Section through the Surface of desiccating coherent Soil.

FIG. 2

The evaporation might be advanced so much that the menisci of capillary water reach the indicated position.

There the superficial soil-granules are surrounded unilaterally by capillary water. An underpressure arises in the interface of soil-granules and capillary water which is compensated similarly as in suspended soil-particles by a pressure between solid and liquid phase. Thereby the water is sucking up the superficial soil-granules. The resulting force of these effects on the individual soil-granule generally is directed perpendicularly to the surface of the soil. The combination of all those forces amounts to the capillary pressure in the solid phase.

According to this interpretation no valuation of the average diameter of the capillary interspaces is necessary for the determination of the capillary pressure; for this rather the granule-analysis is decisive.

8. SUMMARY

Proceeding from the consideration that no physical reality is due to the conception of surface-tension, an explanation of surface- and capillary phenomena which is independent from this conception has been tried in the above explanations. As far as therewith the

liquid is concerned itself no alteration of quantitative relations takes place, and therefore the explanations differ only in methodical respect from the usual contemplation. But an effect of the described interpretation upon the coacting solid substances, especially upon the solid phase in coherent soil exists also in quantitative respect.

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SUB-SECTION I d

STRESS-STRAIN RELATIONS; CONSOLIDATION

1 d 9

DEFORMATIONS AND STRESSES IN THE MEDIUMS WITH INTERNAL FRICTION

J. MANDEL

SUMMARY OF THE FRENCH REPORT.

The author strives to state precisely the basis of the computations about stress distribution in the ground.

10. Through a water containing soil loads are transmitted, partly by the water, partly by the contacts between solid elements. In order to put this fact into a mathematically convenient form, the author defines a statistical contact stress on each surface element. The whole stress-tensor is now the sum of the statistical stress tensor (contact tensor) and the hydraulic tensor. The deformations of the medium (settlings, slidings, breakings) depend not on the whole tensor but on the contact tensor. The well known effects of capillary underpressures or hydrodynamic actions are derived from the equilibrium equations for the contact tensors.

20. May we compute the small deformations of a soil under a load, as if elastic deformations were concerned? This is right when the 3 main stresses given by such a computation are of the same sign. When it is not the case, we may indeed state linear relations between main stresses and main strains, but we must assume that the coefficient relating to the effect of a stress under a strain depends on the sign of

this stress. Thus we are induced to consider 4 coefficients instead of the 2 usual coefficients of elasticity (E : modulus of settling, E' : modulus of swelling, ν and ν' : corresponding Poisson's ratios). On that basis, the author gives the solution for the problem of the equilibrium around a hole in the form of a circular cylinder (wells, tunnels).

30. The previous considerations are applied to the problem of the settling of clayish masses. The author precisely states the question of immediate settling by proving the proposition, valid for plane problems: In a homogeneous or not homogeneous medium, to which in a point M coefficients E, E', ν, ν' belong, immediate stresses and strains are the same as if the medium were perfectly elastic and had in M the coefficients :

$$\nu_0 = 0,5 \quad E_0 = \frac{3}{4} \left(\frac{E}{1+\nu} + \frac{E'}{1+\nu'} \right)$$

The fact that E' is much greater than E explains that the immediate deformation is much smaller than the deformation we should compute by using the theory of elasticity if employing the modulus of settling E (instead of E_0) associated with the Poisson's ratio $\nu_0 = 0,5$.

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