

THE INFLUENCE OF PHYSICO-CHEMICAL FACTORS UPON THE MECHANICAL PROPERTIES OF CLAYS

by

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ABSTRACT

The engineering problems of clay soils are closely connected with the "bulk properties," i.e. shear strength and deformation properties as function of stress conditions and time. These properties are based upon factors in the atomic range and can never be understood without an understanding of the fundamental processes.

The bulk properties of virgin sediments differ from those of chemically or mechanically altered clays (called hypo-metamorphic).

The difference in view generally held by soil mechanics engineers and ceramic research people concerning soil-water systems as built up of minerals in contact with or separated by water, may only be apparent. The water at the mineral surfaces appears to have properties of a solid substance but not the atomic arrangement of ordinary ice. Within a small area, as at the points "of contact," the H's and O's may take the arrangement of a perfect solid. The movement of a corner of one mineral along the plane of another can only take place if flow or creep in the condensed water is possible. In perfect crystals we have only elastic deformation or yielding. The secondary consolidation of clays and the permeability at low hydraulic gradients are discussed as functions of the physics of the water. The influence of temperature and electrolytes upon the properties is suggested as fundamentally important. A plea for further research in the physics and chemistry of surface processes on the various clay minerals is given.

At first I will bring you my most sincere thanks for the honorable invitation to give the Keynote Address at this conference. It is like carrying coals to Newcastle to speak about physical-chemical properties of clays at this university where so many outstanding colleagues have contributed so much to our present state of understanding of the subject.

When dealing with clays we have some few properties that are of paramount interest for practical engineering treatment. We may say that the cash value of soil mechanics is buried in the shear strength, the deformation properties and the water content of a soil as functions of stress conditions and time. These factors involve, however, nearly innumerable problems in the field of pure science. For the practical engineer these problems in

physics and chemistry may seem irrelevant and uninteresting. Even in the engineering soil sciences and in the mathematical treatment of the static and mechanical problems much uncertainty still is involved. The stability problems may seem to be susceptible to engineering mathematical treatment, and foundation engineers all over the world are doing good jobs, leading to an optimal utilization of the subsoil for building purposes, although the fundamental factors in a landslide (Plate 1) may not be understood. The problems in settlement are still less well known, and it is obvious that prediction of settlement rates, especially of what is going on during secondary consolidation, is often unsatisfactory. Settlement phenomena as shown on Plate 2 are therefore subjected to increasing study by the research engineers, and a long series of papers and doctors' theses have appeared during the past few years, none of them claiming, however, so far as I have seen, to have solved fundamental problems of settlement. We may here take the analogy to an engineer working with steel construction. When he knows that his material has a yield value of say 20 tons per in² and given Young's modulus, the engineer may construct an optimal machine. Why the yield value of the steel is 20 tons and not 2 tons or 200 tons per in² does not interest the engineer, as long as he knows that he may with safety use a given value. The theoretical metallurgist, however, is not interested in what the construction engineer is doing with the steel, but in why the properties are as they are; and the metallurgist is interested in which forces act between the single atoms in the crystal and between the crystals in the material. The amount and orientation of dislocations and their movement is today the subject of the greatest interest in all laboratories working with materials. Today we know enough about the laws of metallurgy to predict some few of the properties of an alloy when we know its genesis. Such a prediction is based not only upon experience, but on understanding. In the case of soils we must admit that the conditions are less flattering. To a certain extent it is possible to predict the properties of a material when we know the genesis, but this prediction *always* will be based upon experience, and *never* upon real quantitative understanding.

During the development of modern scientific soil mechanics, and especially during the past four to five years, several papers have appeared pointing to the importance of chemical factors for the prediction of mechanical properties. Most of these papers have been of a qualitative nature, even though numerical values are often given, showing how much the shear strength, compressibility, or sensitivity of the soil is influenced by a given chemical change, or how far the permeability depends upon the physical conditions. This does not mean, however, that soil mechanics has left the applied engineering sciences and entered into the exact sciences. The fact that a conference like this one is held, however, must be taken as an indication that in the future there are possibilities for such a development.

At the Fourth International Conference of Soil Mechanics in London in 1957, I gave as general reporter a plea for more fundamental research. At that time I was criticized somewhat, because, as they said, I wanted to change the conference into a conference in physics instead of a conference in soil mechanics. However, I am still of the opinion that it is necessary to study the single details as thoroughly as possible in order to understand the whole. The scientist who knows more and more about less and less and at last knows nearly everything about nearly nothing is necessary in order to increase the understanding of the whole material.

This symposium is intended to give a general survey as for instance indicated by Plate 3 ("dust of the ground" as seen from some distance), whereas the single scientist may present the results of investigations as Plate 4 (a human skin as seen from a close position); it is all a question of scale, and we must not forget the unity because of the details.

A conference with a title like this is not a unique idea. Last year we had a conference in Australia on the subject "Interparticle Forces in the Clay-Water Electrolyte Systems," published at Melbourne in 1960; and other conferences, regional or international, certainly will come in the future. The physico-chemical treatment of a problem involves consideration of the influence of temperature, pressure, and chemical components upon the properties. In the engineering treatment of clays, we deal with very complex systems of great variability in genetic, mineralogic and chemical factors. The age of the material will vary from more than 500,000,000 years as in the Leningrad and Baltic soft Cambrian clays in the Soviet Union, to recent deposits. Theoretically we know that a fine-grained product represents a higher free energy than a coarsely crystalline substance of the same composition. Thus it seems as though the clays do not represent states of equilibrium. Nevertheless their age may run in hundreds of millions of years. Genetically clays may represent true sediments with or without physical and chemical alterations. They may represent residual products of surface weathering or the result of deep-seated hydrothermal actions on igneous or sedimentary rocks. Mineralogically and chemically there may be great variations in composition, size and relative orientation of the mineral phase, and composition and amount of the aqueous phase. A concise treatment of the physico-chemical properties of clays is therefore meaningless or, at the best, an overwhelming task. We must remember that "many roads lead to Rome." If we can produce a material of given properties in the laboratory, it does not necessarily mean that a natural material of the same properties originated in the same way. In chemical industries, a given product may be synthesized in many different ways. In nature we know that such a mineral as sulfur may either originate through the action of sulfate-reducing bacteria, or by sulfide oxidation, or by volcanic exhalation. A laboratory experiment therefore may tell us how a property may arise,



PLATE 1. — Landslide.



PLATE 2.—Settlement phenomenon, still an unsolved fundamental problem.



PLATE 3.—“Dust of the ground” as seen from some distance.

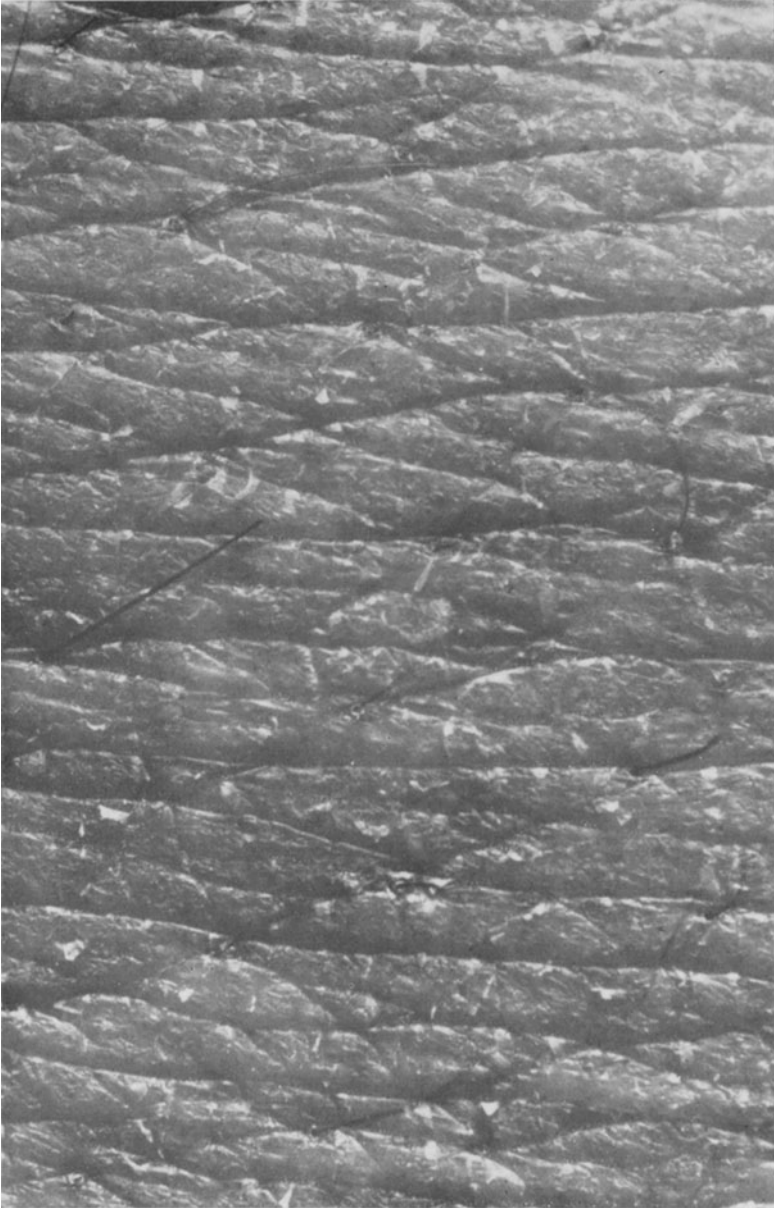


PLATE 4.—The fly's-eye view. "Dust of the ground" closely examined

but not much more. The way into which modern soil mechanics has entered seems, however, to be the right way for further understanding, and I can see no other way to increase our knowledge.

The aim of science is said to be to put the same name on different things. In the case of clays, we in fact lack a nomenclature from which the professional man can grasp the properties when he hears the description or the name. Such a nomenclature may be either genetic or descriptive. If the physical and chemical laws acting in a system were adequately known, a correct genetic denomination would permit complete inference as to the mechanical properties. We are far from this state today. As most scientific terms have acquired special contents through use and wear, it sometimes may be necessary to introduce new terms in order to avoid misunderstanding, although it may overload the vocabulary. In regard to the clays I feel the lack of a term which tells us that the sediments have been subjected to chemical and mechanical action since their formation. We have, of course, the word "overconsolidated" for one special action, but no general term, and nothing to indicate that the mineral phase has been subjected to mineralogical or physical-chemical changes. As the word "metamorphism" is already used by the geologists for severe physical-chemical readjustments, as the transformation from slate to schist or gneiss, I propose the term "hypo-metamorphism" for those minor changes that may transform a virgin clay into a clay or shale of a different state, but not changing it into a nonclay rock. Such processes take place in all clays susceptible to flow or diffusion in the aqueous phase. I think this conference will to a certain extent deal with what I have called hypo-metamorphism.

It is generally accepted that the physical properties of soils are not constant, but depend upon changes in external and internal factors. The effect of adding, or subtracting, water to the soil and the influence of chemicals in soil stabilization are well known, though the mechanism may be obscure. Scientific treatment of clays has been approached from at least three frontiers, namely from engineers in soil mechanics, from agriculturalists, and from ceramists. There is an apparent conflict of opinion between investigators with a ceramic background, who tend to regard the particles in a plastic clay as separate solid particles with a water film between them, and the soil mechanics people, who tend to regard soils as built up of contiguous minerals in a skeletal structure with pore water in the voids (Williamson, 1960). The conflict in opinion may be apparent rather than real. It all depends upon how the innermost water adjacent to the minerals is to be regarded. A fundamental understanding of the points of contact between two minerals is necessary in order to understand the mechanism of any change in shape of a soil. As shown by Hvorslef (1937), the strength of a remolded clay may be expressed by the generally valid equation,

$$S = C_e + \sigma' \tan \varphi_e$$

where C_e is a material constant depending upon the water content at failure only, σ' is the effective normal stress on the plane of failure, and φ_e is the true angle of friction.

This equation is derived for and only valid for consolidated clays without subsequent changes in composition of the minerals, or cementation, and it is not to be taken literally in anything but virgin clays. The recent finding by Leonards and Ramiah (1959) indicates that a pseudo-overconsolidation effect may develop in a soil that is left at a given stress condition for a (geologically speaking) very short while. This is a general phenomenon. It appears that after a period of rest comparatively rigid bonds develop, which need a certain increased critical stress to break down. Terzagi (1925) has attributed such a rigid bond to the water surrounding the minerals, while Tan (1957) believes that the rigid bond develops between mutually connected "plate shape clay particles."

The same type of effect recently has been noticed in nature by Bjerrum and Wu (1960) for some Swedish clays. They explain the effect by assuming cementation between the minerals. By triaxial apparatus tests they find an apparent overconsolidation, which amounts to several kilograms per square centimeter, above the geologically possible consolidation pressure. From their paper it may be inferred that they regard precipitation of calcite or calcium-bearing minerals around the points of contact of the illite flakes as the reason for this apparent overconsolidation. There is, however, no direct confirmation of this hypothesis, and perhaps the difference in opinion between Terzagi's and Tan's and Bjerrum and Wu's opinion is more apparent than real. Some kind of rigid bond is undoubtedly present, but the nature of these bonds is still open for discussion. There is sufficient indication that some kind of rigid bond may develop in flocculated as well as in the remolded clays after some time, even in clays that are subjected to a consolidation process.

In virgin clays, the mutual arrangement of the minerals is assumed as by the Goldschmidt-Lambe concept (Fig. 1) and by Tan (Fig. 2) or as actually observed by the blue Oslo clay (Plate 5). Any deformation in such a clay must necessarily involve mutual displacement of grains. A point on the edge of one mineral must move along the plane of another, as the elastic deformation of each mineral plate will never be sufficient to permit the large consolidation ratios which are often found. Any mutual movement of mineral grains must involve either a yield or a creep in the place adjacent to the plane along which the point is moving, independently of whether it is assumed that the silicate minerals are in actual contact, *i.e.* that the distance between an oxygen atom in the tetrahedral layer of one mineral and the oxygen atoms in the crystal lattice of the adjacent mineral is about 2.8 Å, or it is assumed that the two silicate lattices are separated by some layers of oxygen and hydrogen, called adsorbed or oriented water.

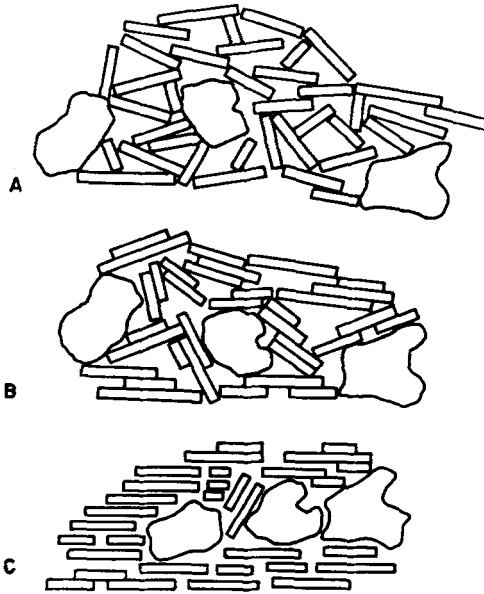


FIGURE 1.—The Goldschmidt-Lambe concept of cardhouse structure, redrawn from T. William Lambe, *The Structure of Inorganic Soils*. A, Undisturbed, salt-water deposit; B, Undisturbed, fresh-water deposit; C, Remolded.

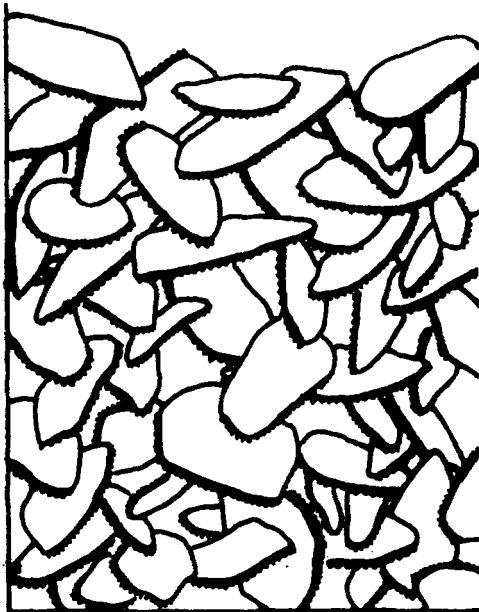


FIGURE 2.—Schematic picture of clay network (Tan, 1957).

Concerning the existence and effect of adsorbed oriented water upon the clay mineral surface, divergent opinions have been expressed. However, there is today hardly reason to believe that the border between the clay mineral and the surrounding water is abrupt. As pointed out by Forslind (1952), the distances between the oxygen atoms in a silicate layer and in a hexagonal water lattice nearly fit each other. Low and Anderson (1958) have shown through a series of beautiful experiments that the density of the water decreases with decreasing water content. Yamaguchi (1959) has shown that in some Japanese clays the apparent specific heat of the mineral phase of clay increases rapidly with decreasing water content, assuming constant specific heat capacity of the water phase as equal to one. Likewise the electric resistance of the clays is higher than theoretically calculated from the components, indicating a water phase of abnormal properties. These abnormal specific heats are higher than found by several other investigators, for instance on the Norwegian clays. However, the mutual influence between minerals and water is fairly well established.

Pickett and Lemkoe (1959) have used radio frequency spectroscopy to study nuclear magnetic resonance of water in clays. Their findings prove that the bond strength in the water increases rapidly with decreasing water content. Because of the proportionality between the line width and the reciprocal of the relaxation time, Pickett and Lemkoe, using James Clark Maxwell's theory for viscosity, assume proportionality between the line width in microwave resonance and the viscosity of the water of the clays. Their values fit very well into the viscosity values calculated by us based upon deuterium diffusibility in the clay water. The values found or calculated by Pickett and Lemkoe, namely 1600 mG for a nearly dry sodium montmorillonite and 950 mG at 3.46 percent water as compared with 4000 mG for ice at -2°C , indicate that the average of the water in clays is much less ordered and less strongly bound than the water molecules in ice crystals at -2°C , but very much more strongly bound than in ordinary water. Their conclusion that the viscosity of the liquid phase will give a negligible contribution to the shear strength of a wet clay may be discussed in the light of their own findings. It seems obvious that most of the water in a clay has no real rigidity that will give any shear strength. The water in the vicinity of the minerals, however, has quite different properties. There can be no doubt that the minerals influence the water, and vice versa. As this influence is not quantitatively known, I take the liberty to present it through an etching by the Dutch artist Escher (Plate 6).

The clay minerals do not represent perfect crystals in the strict sense of the word. A perfect crystal is electrically neutral. However, because of the small size of the clay minerals there will be unsatisfied bonds on the broken edges. Furthermore, the atomic substitutions in the lattice of the crystal involve cations of lower valency than those necessary for electro-neutrality.

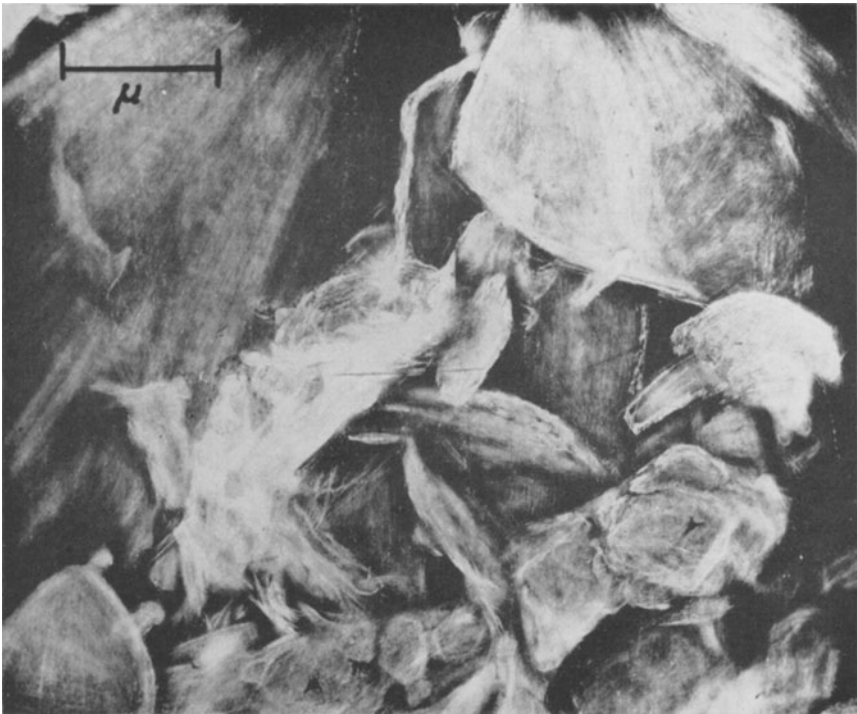


PLATE 5.—Electron micrograph showing mutual arrangement of minerals in the blue Oslo clay.

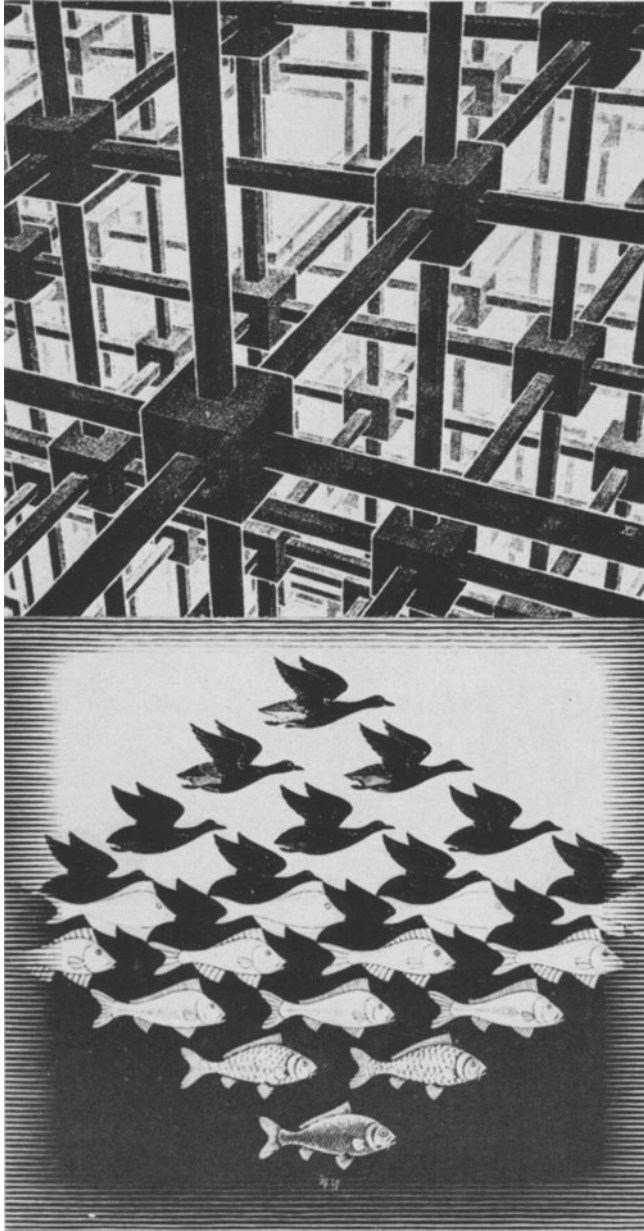


PLATE 6.—Opposing concepts of structure of bound water. Drawings by M. C. Escher.

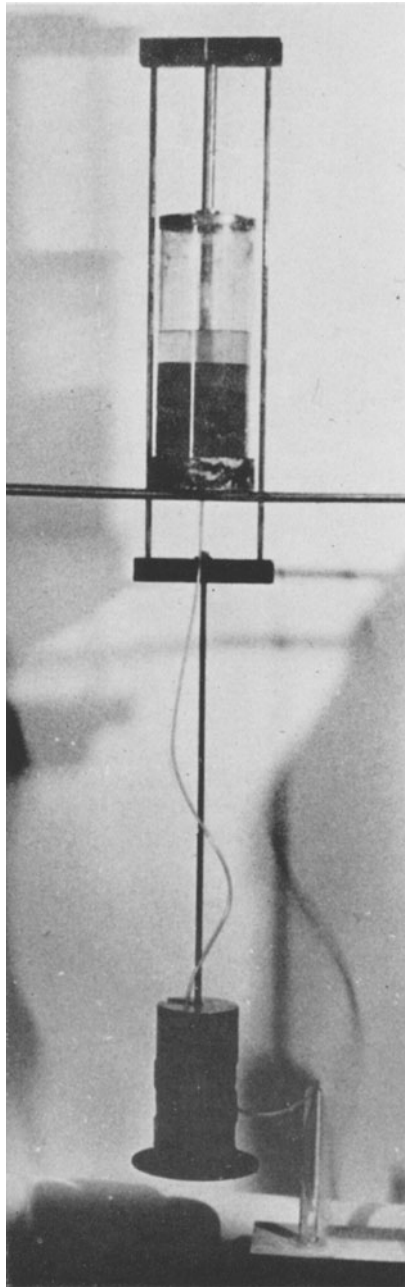


PLATE 7.—Equipment for sedimentation and consolidation tests.

These factors make the real particle (which is an imperfect clay crystal) behave, therefore, as a large insoluble weakly charged ion, whose surface has a negative charge. These particles are distributed in water that is not chemically pure, and never can be. In the water surrounding the minerals counter ions are distributed, interrupting the arrangement of the ordered water lattice. The classic Gouy-Chapman theory of the diffuse double layer, which proved very stimulating when introduced in soil mechanics, has, however, failed to explain several of the mechanical properties of soils. At best, the theory consequently must be modified owing to the difficult conditions. This was discussed by Low (1959).

The evidence cited by Low makes two of the basic assumptions of the double layer theory questionable. These assumptions were: (1) the potential energy of the exchangeable cation is influenced only by the electric field of the clay particle; and (2) the clay surface itself does not attract water. Further, in normal calculations intending to test the double layer theory the assumption is made that the aqueous phase has the same dielectric constant as normal water. This assumption is not justified by the experimental evidence. Bergeth's (1960) electrokinetic studies on nonswelling and swelling clay minerals in the colloidal state proved that the electrophoretic movement for nonexpanding minerals (chlorites) decreased regularly with increasing electrolyte concentration in the pore water, whereas for expanding minerals (montmorillonites) the electrophoretic movement increased with increasing concentration of sodium and potassium chlorides as well as with sodium and potassium sulfates. His results showed further that the sulfate anions had a stabilizing influence upon the sodium-charged chlorite particles. Measurements of the pH of concentrated slurries of chlorite on addition of sodium sulfate or potassium sulfate gave a marked increase in the pH. It is probable, therefore, that even in diluted hydrosols the polarizable sulfate ions may exchange with the OH^- on the surface of the chlorite particles, thus giving a higher negative charge. An increase in the cation concentration of the surrounding medium, however, gave a decrease in the zeta potential and caused coagulation. The increase in electrophoretic velocity of movement for sodium-charged montmorillonites, but not the chlorites, with increasing concentration of sodium chloride, potassium chloride, sodium sulfate and potassium sulfate may be explained by a shrinkage of the distance between the montmorillonite lamellae, thus giving a smaller total surface, and quicker movement in the electric field because the particles are smaller and the charge density may be greater.

This leads to a discussion of the mechanical properties of montmorillonitic and illitic clays dependent upon the electrolytes of the pore water. At the Fourth International Congress for Soil Mechanics the liquid limit of montmorillonitic and illitic clays was discussed in relation to the polarizability of the exchangeable cations (Rosenqvist, 1957). Data were given for a

Hungarian bentonitic clay and two Norwegian illitic clays (Fig. 3). It was demonstrated that the liquid limit increases with increasing size of the monovalent cation, thus $Li < Na < K < Rb < Cs$ in the case of the illitic clays. The gradient of increase was proportional to the content of illite and to the ion exchange capacity. In the montmorillonitic clays it was found that the liquid limit dropped from Li to Na and from Na to K, but increased

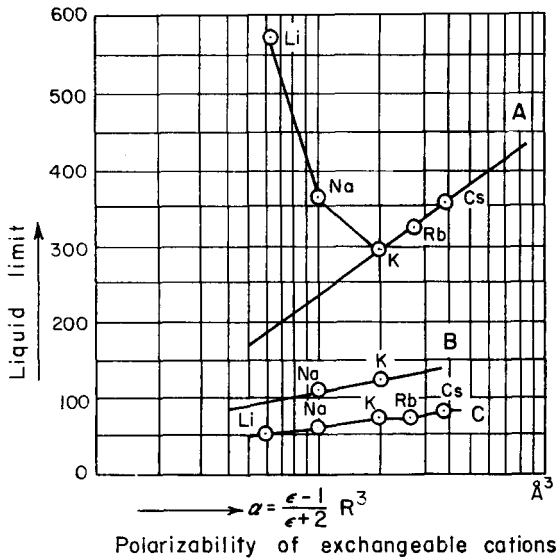


FIGURE 3.—Relation between liquid limit of montmorillonitic and illitic clays and polarizability of the exchangeable cations. *A*, Montmorillonite, BEC = 110 meq/100 g; *B*, ≈90 percent illite, BEC = 30 meq/100 g; *C*, ≈40 percent illite, BEC = 17 meq/100 g.

on passing from K to Rb and from Rb to Cs. As the liquid limit of a clay expresses the difference in water content between a clay–water mixture of low shear strength and the material dried at 110 °C infracrystalline as well as infracrystalline water is involved in montmorillonite, whereas in illites the amount of infracrystalline water is insignificant. As the amount of intercrystalline water and the liquid limit are dependent upon the bonding strength between the minerals, this amount will increase in the following manner: $Li < Na < K < Rb < Cs$, being a function of such forces. The infracrystalline water varies in the manner $Li > Na > K = Rb = Cs$. When these two curves are summed up, the variation of the liquid limit is about as shown in Fig. 3.

In order to investigate the effect of infra- and inter-crystalline water upon the shear strength of montmorillonitic and illitic clays, a series of

sedimentation and consolidation tests have been carried out. The equipment used is the same as that described by Bjerrum and Rosenqvist (1957). The sedimentation was carried out in cylinders having a cross-sectional area of 140 cm² (Plate 7). Natural illitic clays and the montmorillonite referred to above were used. The cylinders contained a solution of sodium chloride containing 13.5 g sodium per liter. The sediments were prepared from a suspension of the respective clays which was added to the cylinders in small portions during one week in the case of the bentonites and in two weeks in the case of the hydrous mica clays. The sediments then were slowly consolidated by increasing loads in small steps during five months, and left for consolidation for another six months, at full load. The settlement rate had then decreased practically to zero, and the actual experiments could start. In half of the cylinders, the supernatant sodium chloride solution was removed and replaced by potassium chloride solution. At the same time a slight underpressure of about 0.1 atm was applied to the bottom of the sediments. The cylinders were left in this state for 26 months before further examinations were undertaken. The main results are included in Figs. 4 and 5, which show variation in shear strength in the undisturbed and remolded state for both

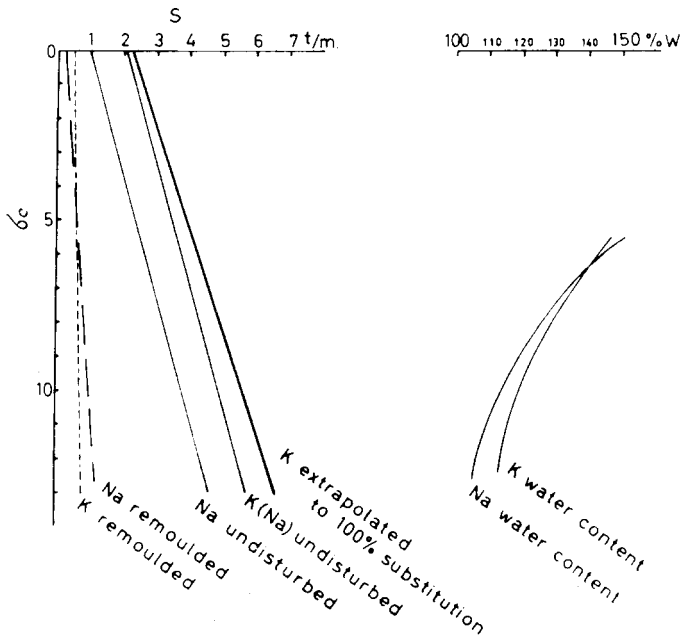


FIGURE 4.—Shear strength of montmorillonite clay as a function of the load and alkali ion. S = undisturbed, undrained shear strength; W = water content in percent of dry matter; c = effective consolidation stress, i.e. weight of overburden \div pore water pressure.

types of clay as a function of the load and the alkali ion substituted¹. The substitution of sodium by potassium involves in illites an increase in the undisturbed as well as in the remolded strength. The sensitivity decreases from an average of about 7.1 in sodium clays to less than 4.5 in potassium

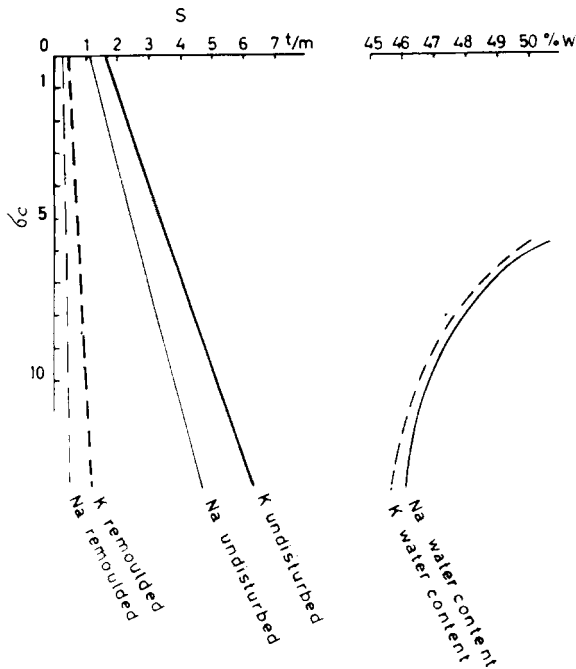


FIGURE 5.
Shear strength of illite
clay as a function of the
load and alkali ion.

clays. In the montmorillonitic clays the substitution is not complete. It therefore seems appropriate to augment the increase in undisturbed shear strength observed in incomplete substitution. The most probable value for the shear strength of the remolded potassium clay is about half of its value in the sodium state. As a consequence of this calculation it is found that the sensitivity increases from 4 in the sodium montmorillonite to 14 in the potassium montmorillonite.

In the investigation of the swelling properties of the clays, X-ray diagrams were taken of the montmorillonite sediments in their undisturbed state on broken vertical sections through the clay, in order to determine the basal plane distance and the randomness of mineral arrangement. The study showed that the randomness of the mineral was nearly 100 percent complete. A back reflection diagram showed no preferential orientation of the basal planes of the minerals. The result of the investigation was that the $hk0$ values of the montmorillonites were unaffected by the substitution,

¹ The clay was remolded with a spatula. K and Na were determined by flame photometer.

whereas the 001 values had undergone a marked change from a basal plane distance of 20.1 Å in the sodium montmorillonite consolidated at 11 tons per m² to 16.35 Å after partial substitution by potassium. The distances found by X-ray examination indicate that by the given consolidation the montmorillonite in the sodium state possesses a tri-molecular layer of water between the backbone sheets of the montmorillonite structure, and two molecules in the mixed sodium-potassium state. Expulsion of water corresponding to about 18 percent of the volume of the minerals has taken place. This water has been transferred from internal parts of the single crystals to the pore water, whereas the distance along the *a* and *b* axes has not changed. As the total water content of the clays is unaffected by the replacement, we are dealing with a case in which no consolidation has taken place during substitution, but minerals are transformed from relatively thick plates into thinner plates. The points of contact between the single minerals have been left unchanged, but their bonds have increased in strength. By remolding, the thinner potassium montmorillonite plates are distributed in more water than are the sodium clays: hence the low shear strength of the remolded paste.

The substitution experiments prove the connection between the composition of the electrolyte, and consequently the ionic state of the minerals, and the mechanical properties of the soil. The sensitivity by remolding is one of these mechanical factors which have been the chief object of investigations carried out in Norway in the past decade. The simplest possible chemical change is what takes place in some Scandinavian quick clays. Here we have a replacement of saline water by fresh water. In illitic clays, this involves a decrease in the undisturbed shear strength, and a pronounced increase in the sensitivity, provided no other chemical or mineralogical changes take place. With montmorillonitic clays such a simple replacement will give the opposite effect.

It is not only by leaching, however, that the sensitivity may arise in illitic clays. Even by addition of certain electrolytes, for instance phosphates, silicates and other dispersants, the sensitivity may increase, as earlier described by Rosenqvist (1955) and Söderblom (1959). In such cases it is mainly the anions that are active. But even changes in the cations from highly polarizable cations to less polarizable cations may lead to the same result; although no examples of such replacement are known in nature, it is performed in the laboratory. The opposite effect, however, is very frequent, namely the replacement of sodium by potassium. This change takes place in the weathered crusts of all Scandinavian marine clays, where the potassium ions are furnished by the weathering of potassium-bearing minerals. The mechanical properties thus change similarly to those described in the above-mentioned case. Many of the properties of the weathered crusts of the Scandinavian clays are similar to those of the artificial clays,

whereas the mixed sodium-potassium montmorillonites resemble the Taqubaya-clays of the Mexico City sediments, as described by Zeevaert (1957) and Foreman (1955). The weathered crust of the Scandinavian marine clays and the clays of Mexico city originated through partial weathering of eroded material. As the liquid phase of a sediment will normally change in composition owing to natural processes during geological time, we are concerned here with a case of hypo-metamorphism.

The consolidation properties of clays have been shown to be very dependent upon chemical factors. Thus a leached Scandinavian marine clay, which is transformed into a quick clay, is much more compressible than it would be in the saline state, although leaching according to the double-layer theory will increase the repulsive forces between the minerals. In a flocculated sediment of high water content, consolidation does not, however, involve a major increase in the total repulsion, as the repulsive forces decrease by the square of the distance. Consolidations in a stacked card-house structure must involve a movement of the points of contact along the planes, and the total repulsive forces increase less during consolidation than they would have if the minerals had a parallel arrangement. In the artificial illitic and montmorillonitic clays described earlier, the much greater compressibilities in the montmorillonites than in the illites is unquestionable.

We now return to what happens at the points of contact during consolidation. As long as consolidation follows the hydraulic model, the edge of the one mineral seems to move freely though perhaps influenced by a high viscosity of the water on the plane, but still it moves along the plane of another mineral. This movement may or may not be Newtonian. During the secondary consolidation, the movement obviously depends upon an obstacle different from the viscous flow. It may here be suggested that this movement is analogous to what is called "creep" in other material, which again depends upon a climbing effect in the dislocations of the imperfect solid state. When the consolidation stops because of rigid bonds, we may either have developed a new solid phase at points of contact, or, what is possible and may act as a working hypothesis, the sum of a few hundred molecules of water in the vicinity of the point of contact may represent the perfect arrangement with no dislocations; and, as known from solid state physics, a perfect crystal does not creep, but may yield, when the shear stress is above a certain limit. By lower stresses, it may be elastically deformed, but it will not creep. It may be that the time effects on the recovering of strength depend upon a slow decrease in the amount of imperfections in the more or less oriented water. Seemingly this subject can be dealt with only by a highly specialized scientist in the field of theoretical chemistry. I do not know any work done on the angular distortion and internal stresses in oriented water which gives a critical value for development of dislocations, but I suppose that even this problem is susceptible to scientific attack and solution.

In about a hundred stereoscopic photos of Scandinavian virgin marine clays I have never observed anything resembling a domain structure. In the clays from the firm crust, however, *i.e.* in hypo-metamorphic clays, cluster structure and fissures are abundant. Still it seems as if even in virgin clays (Hansbo, 1960), the permeability is a function of hydraulic gradients. Hansbo gives the picture shown in Fig. 6 (Hansbo's Fig. 29). Such a de-

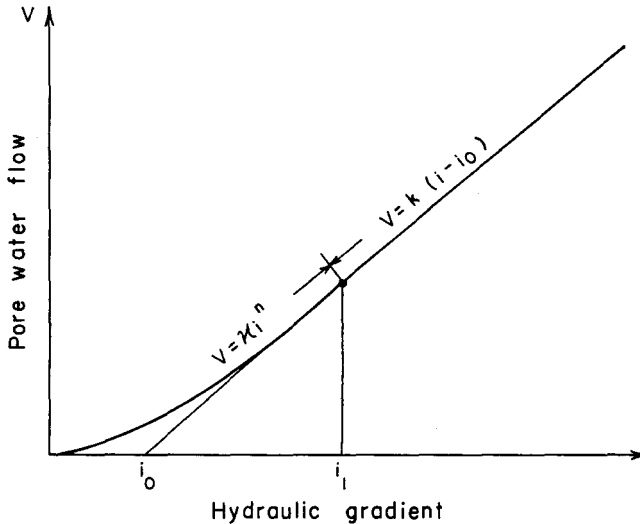


FIGURE 6.—Permeability as a function of hydraulic gradients (after Hansbo, 1960).

viation from Darcy's law might be explained by a domain structure, but equally well by the texture actually observed in virgin clays, assuming statistical variations in the pore sizes and an exponential increase in the viscosity of the water with decreasing distance from the mineral surfaces. Altogether, these considerations may lead to a still newer rheologic model for consolidation of clay skeletons.

Since the presentation of Buisman's (1936) formula several rheological models for consolidation have been published. It seems to me as though the physical-chemical knowledge we have today indicates modification of the mathematical models by Tan (1957) and Murayama and Shibata (1959) (Fig. 7). For the first, the dashpot must be of a non-Newtonian type, and the perforated lid presented in Tan's model ought to have valves opening at various pressures below a certain limit.

Some few points as to the influence of changes in temperature:

(1) At temperatures somewhat below 0°C a new phase, ice, begins to develop at the expense of the aqueous phase of the clays. The amount and mode of occurrence of the ice phase depend upon the soil type and the temperature.

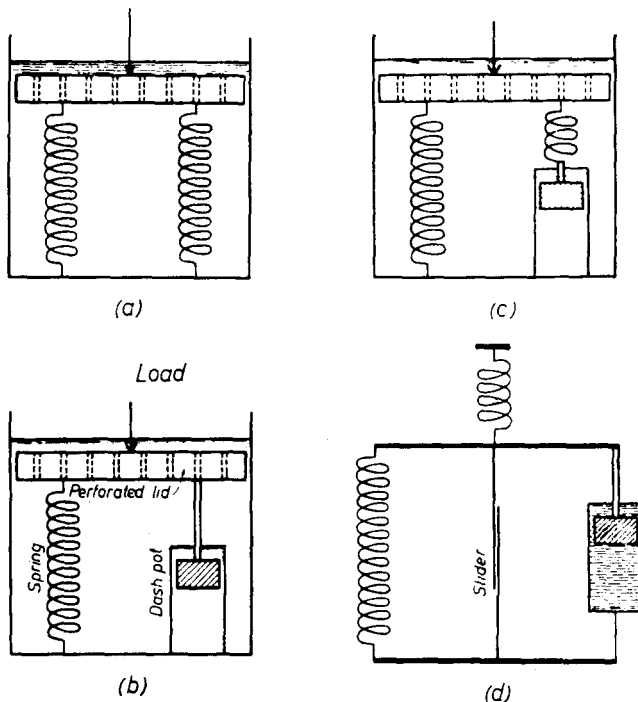


FIGURE 7.—Rheological models of clay skeleton. (a) Biot (1935), (b) Taylor (1942), (c) Tan (1957), (d) Murayama and Shibata (1959).

(2) At temperatures above that necessary to form ice and also at temperatures where parts of the aqueous phase are present as ice, a change in the temperature will involve several effects as the dV/dT changes in water and in the solid phases at different rates. Lowering of T above $+4^\circ\text{C}$ may cause an underpressure and below $+4^\circ\text{C}$ an overpressure in the pore water.

(3) As the water near the minerals has a greater specific volume and a positive heat of formation, this phase according to the Clausius-Clapeyron equation normally will increase at the cost of the "free water" with decreasing temperatures. The diffuse double layer and the repulsive forces likewise will be influenced by changes in temperature.

Altogether these and other factors partly acting in the same direction, partly counteracting each other, seem in most cases to increase the shear strength of a clay body by decreasing T .

REFERENCES

- Anderson, D. M. and Low, P. F. (1958) The density of water adsorbed by lithium-, sodium- and potassium-bentonite: *Soil Sci. Soc. Amer. Proc.*, v. 22, pp. 99-103.
- Bergseth, Harald (1960) Elektro-kinetiske studier av kloritt og montmorillonitt i kolloid tilstand: M.Sc. Thesis, Oslo University.

- Biot, M. A. (1935) Le problème de la consolidation des matières argileuses sous une charge: *Ann. Soc. Sc. Bruxelles*, v. 55.
- Bjerrum, L. and Rosenqvist, I. Th. (1956) Some experiments with artificially sedimented clays: *Geotechnique*, v. 6, no. 3, pp. 124-136.
- Bjerrum, L. and Wu, T. H. (1960) Fundamental shear strength properties of Lilla Edet: *Geotechnique*. In press.
- Buisman, A. S. K. (1936) Results of long duration settlement test: *Proc. 1st Int. Conf. Soil Mechanics and Foundation Engineering*, v. 1, pp. 103-106.
- Foreman, F. (1955) Palynology in southern North America II. Study of two cores from lake sediments of the Mexico City basin: *Bull. Geol. Soc. Amer.*, v. 66, pp. 475-510.
- Forslind, E. (1952) The clay water system.—II. Water adsorption and cation exchange in montmorillonite: *Svenska Forskningsinstitutet för cement och beton vid Kungl. Tekniska Högskolan i Stockholm*, Handlingar, no. 17, pp. 3-11.
- Hansbo, Sven (1960) Consolidation of clay with special reference to influence of vertical sand drains: Ph. D. Thesis, Chalmers Tekniska Högskola, no. 25, Stockholm. *Swedish Geotechnical Institute, Proc.*, no. 18, pp. 1-159.
- Hvorslev, M. J. (1937) Über die Festigkeitseigenschaften gestörter bindiger Böden: *Ingeniørvitenskabelige Skrifter*, København, A, no. 45, pp. 1-159.
- Interparticle Forces in Clay Water Electrolyte Systems (1960) Seminar Proc., *Commonwealth Scientific and Industrial Research Organization*, Melbourne.
- Leonards, G. A. and Ramiah, B. K. (1959) Time effect in the consolidation of clays: *Symposium on Time-Rate on Loading in Testing Soils*, A. S. T. M. Annual Meeting.
- Low, P. F. (1959) Physical-chemical properties of soil. Ion exchange phenomena (Discussion to A. W. Taylor's paper): *Soil Mechanics and Foundation Division, Amer. Soc. Civil Engineers*, v. 85, pp. 79-89.
- Murayama, S. and Shibata, T. (1959) On the secondary consolidation of clay: *Proc. Japanese Society for Testing Material, 2nd Cong.*, pp. 178-181.
- Pickett, A. G. and Lemkoe, M. M. (1959) An investigation of shear strength of the clay water system by radio frequency spectroscopy: *J. Geophys. Res.*, v. 64, pp. 1579-1586.
- Rosenqvist, I. Th. (1958) Physical-chemical properties of soil water system (discussion): *J. Soil Mechanics and Foundation Division, Proc. Amer. Soc. Civil Eng.*, pp. 31-53.
- Rosenqvist, I. Th. (1955) Investigations in the clay-electrolyte-water system: *Norwegian Geotechnical Institute Pub.* 9, pp. 3-120.
- Rosenqvist, I. Th. (1957) Soil properties and their measurements: *4th Int. Conf. on Soil Mechanics and Foundation Eng.*, Gen. Rept., Div. 1, v. 2, pp. 427-432.
- Söderblom, R. (1959) Aspects on some problems of geotechnical chemistry: *Geologiska Föreningen i Stockholms Förhandlingar*, v. 81, no. 4, pp. 727-732.
- Tan Tjong Kie (1957a) Discussion: *Proc. 4th Int. Conf. on Soil Mech. Found. Eng.*, v. 3, p. 87.
- Tan Tjong Kie (1957b) Secondary time effects and consolidation of clays: *Academica Sinica Harbin*, China, Monograph, pp. 1-17.
- Taylor, D. W. (1942) Research on consolidation of clays: *Mass. Inst. Techn. Pub.*, Dept. Civil and Sanit. Eng., ser. 82.
- Terzaghi, K. (1925) *Erdbaumechanik auf bodenphysikalischer Grundlage*: Deuticke, Lpz., 399 pp.
- Williamson, W. O. (1960) Particle orientation in a kaolinite-illite clay caused by deposition or deformation. Some shrinkage and mechanical properties of the oriented aggregates so formed: Paper, *Interparticle Forces in Clay-Water Electrolyte Systems*, Melbourne, Div. 2, pp. 40-65.
- Yamaguchi, Schinichi (1959) On the sensitivity of clay: *Disaster Prevention Research Institute*, Kyoto University, Kyoto, Japan, Bull. 28.
- Zeevaert, L. (1957) Foundation design and behaviour of Tower Latino Americana in Mexico City: *Geotechnique*, v. 7, no. 3, pp. 115-133.