

STUDIES ON THE PROPERTIES AND FORMATION OF QUICK CLAYS

by

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ABSTRACT

In a natural clay, the occurrence of a high sensitivity, i.e. a high quotient between the shear strength of the undisturbed and remolded soils respectively, under undrained conditions, is connected to thixotropic effects and to "quickness".

The general composition of the soils in which quick clay occurs is described, and mention is made of the occurrence of non-argillaceous rock fragments in a matrix of clay particles. Illite is the main clay mineral. Quickness occurs both in salt-leached, marine deposited clays and in clays deposited in fresh water. The pore water of these clays is low in electrolytes and undecomposed organic material. It is found that quick clays often occur near peat and similar humic deposits. Also briefly discussed is the internal stress distribution in natural clays under various consolidation conditions, the structure of quick clays and their conditions of formation. The consistency of clays is considered, as is the stability and coagulation conditions of suspensions. This is followed by a commentary on physico-chemical effects contributing to the formation of quick clays under natural conditions, and a discussion of the salt-leaching theory and the theory on the effect of peptizing agents.

In the discussion, the author draws parallels between the coagulation and the thixotropic phenomena, and between the stability and dispersion of suspensions and the quickness.

INTRODUCTION

DISTURBANCE of a natural clay will change its strength. The quotient between the shear strength of undisturbed clay, as determined by tests performed under undrained conditions, and that of completely remolded clay is known as *sensitivity*. There are two main reasons for the occurrence of a high sensitivity, namely a reversible effect, *thixotropy*, and an irreversible condition, known as *quickness*.

A *quick clay* is defined as a clay that when undisturbed has a certain shear strength and can be regarded as a solid body, but which when remolded can be regarded as a liquid. In practice, a clay is called "quick" when its sensitivity exceeds a certain number, usually 30–50, depending on the method used for the determination of the shear strength.

When a clay is remolded, the position of the particles and the balance of the interparticle stresses is disturbed. Remolding brings about an

increased degree of parallel orientation of particles (texture) and consequently, as a rule, a decrease in shearing resistance.

In a thixotropic system, the particles and the water—at rest after remolding—become reorientated in a new state of equilibrium. During this process, the changed stresses in the solid phase must attain new values, which give rise to stresses in the liquid phase which appear in the form of suctions. This indicates a regain in strength, thixotropy, dependent on the orientation of the particles and the water. This regrouping is a time-consuming process, which the author regards as a coagulation process. It could be said that the greater the cohesion in the clay, in a certain range of water content, the greater, usually, is the strength regain.

In a quick clay, which can be regarded as a solid in dispersion, a reversible change of the shear strength can occur by changing the water content. Such changes occur therefore in practice. Re-establishment of strength at constant water content accordingly requires special measures.

The contents of this article will be chiefly limited to investigations which in general have been carried out in Sweden, and in particular by the Swedish Geotechnical Institute (SGI), regarding the properties, including certain definitions, of quick clays and theories of their formation. The conclusions presented here may well be applicable to a large number of similar quick clay areas within Fennoscandia and other regions.

GENERAL COMPOSITION OF THE CLAYS

In the Swedish Quaternary clays under discussion, the coarser particles of rock fragments generally consist of quartz or feldspar. The finer particles consist mainly of hydrous mica, similar to illite, and of small quantities of the above-mentioned minerals. The illites in the Swedish soils may be of pre-glacial origin but may also consist of other transformed minerals. Tamm (1928) demonstrated that clays obtained by wet pulverization of quartz and feldspar are lacking in plastic properties whereas clays of mica origin show typical plasticity.

Studies on the mineral composition of the Swedish sedimentary clay soils have been performed by Wiklander (1950), Collini (1950) and Kerr (1963). These authors emphasized the predominance of illite. The occurrence of a certain amount of other minerals in the quick clays is mentioned by Kerr.

The composition of Finnish clays shows an apparent similarity to that of the Swedish clays, cf. Soveri (1957) and Keinonen (1963). In Norway, Rosenqvist (1949, 1960 and other publications) mentioned not only the predominance of illite but also the occurrence of chlorite. The Norwegian clays are generally coarser than the Swedish and Finnish clays.

Most of the clays found in the Swedish west coast areas are marine clays, deposited in salt water. Thus, the liquid phase of the clays contains varying amounts of salts, depending on the degree of leaching or diffusion. In the

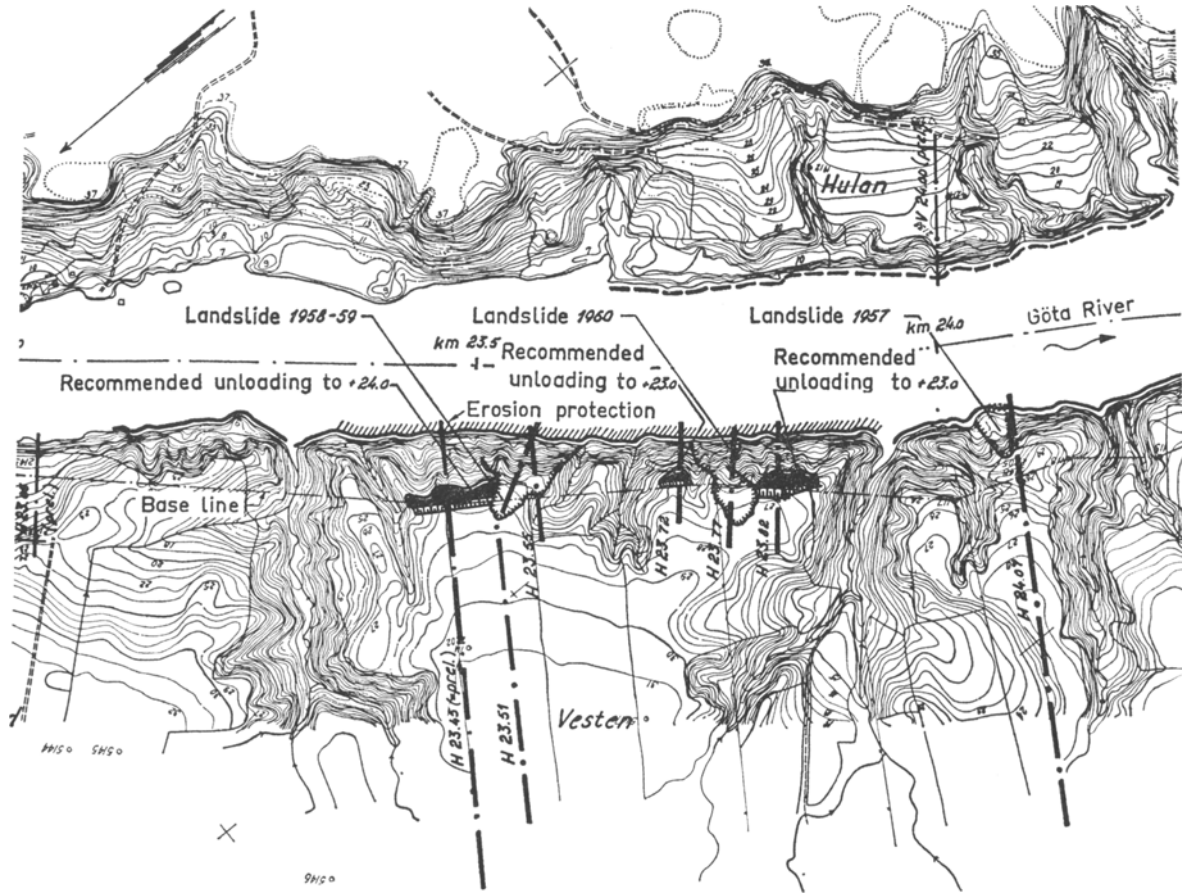


FIGURE 1.—Map of a terrain in the Göta River Valley with active river erosion and landslides occurring every now and then in deposits with quick clay.

Norwegian clays, which as a rule are also salt water deposited, G. Holmsen observed that quick clay has not been found in deposits with a high salt content. This condition appears to apply also to Sweden. Nor have any similar electrolytes been found in any greater quantities in the quick clays.

Fig. 1 is a map of a marine clay area with quick deposits in the Göta River Valley, where landslides occur frequently. Proposed protection works are shown in the figure.

The clay deposits found in the Swedish inland and on the east coast may be salt-water deposited, but are often deposited in brackish or fresh water. In the former types of clay, the electrolyte content varies greatly owing to the varying conditions of leaching and diffusion. The glacial fresh water clays are generally stratified with bands, in the case of silty or sandy layers these are called varves.

The postglacial clays contain organic components in quantities which are extremely important, particularly for the water-binding properties of the soil. Bands are often found in the postglacial clays, indicating a sulfide enrichment. The glacial clays also contain organic components, although to a lesser extent. In localities where the organic components occur as fibrous or as otherwise relatively undecomposed material, quick clays appear to be rather rare. Where the organic components are in a state of advanced decomposition and the content of humic substances (peat humus) is high, quick clays occur so frequently that the humic substances require special attention.

Some of these deposits have been specially noted by the Swedish State Railways, cf. Jerbo and Hall (1961) Fig. 2.

The occurrence of humic and similar components in the Swedish clays is frequent and has been studied by Odén (1919). This author has placed the humic acids in different groups according to their solubility and the solubility of their salts, and also with regard to their color. Aschan (1908) made an inventory of the occurrence of humus in Finnish soils. Mattson and Gustafsson (1937) and Van Beneden (1958) among others have presented information on some protective colloid effects of the humic substances.

After the clay has been deposited it is sometimes subjected to erosion which, in certain places, has removed a large quantity of clay. However, land heave has taken place concurrently and the clays can therefore, as a rule, be regarded as "normally" consolidated for the soil load. In some cases the clays may be slightly overconsolidated, for example in earth layers below or besides waterways, which have been subjected to scour. The clays below the ground-water surface are generally water-saturated, except in places where there is a sporadic occurrence of gases and a high content of organic material which is not completely decomposed. The influence of organic matter on differential thermal analysis of Swedish clays is discussed by Silfverberg (1955).

Above the ground-water surface, the clays, especially in Sweden and

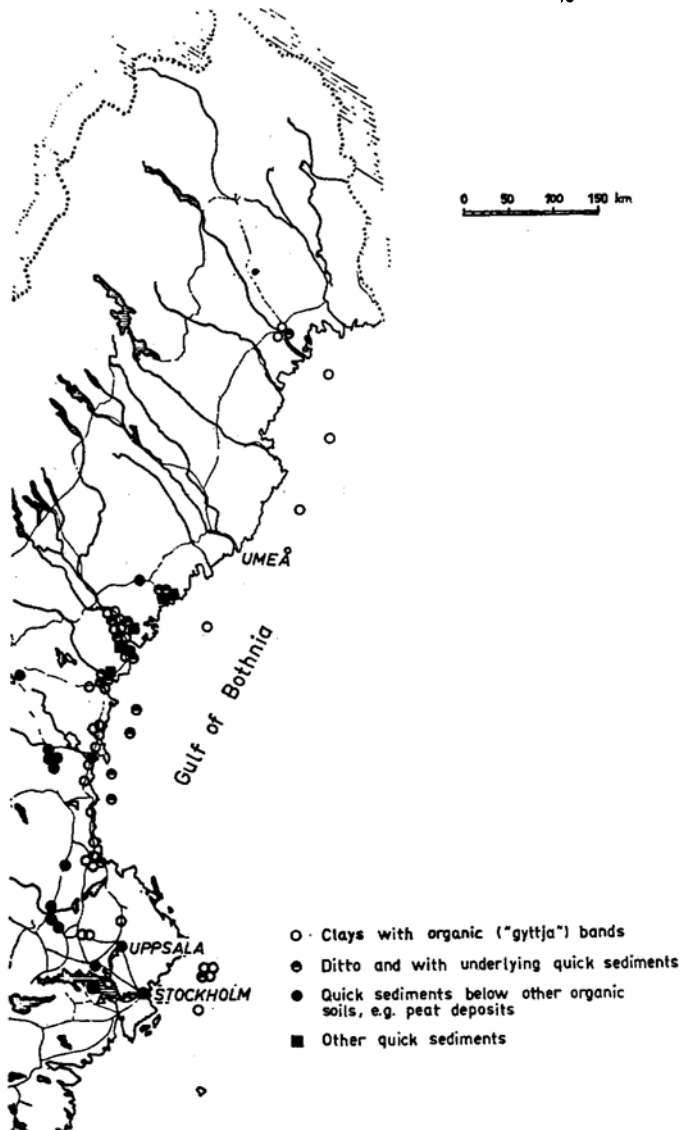


FIGURE 2.—Map of the Swedish north coast, showing quick soils (near to the Swedish State Railways lines) influenced by the various conditions of sedimentation and surroundings.

Finland, have formed marked dry crusts that are the result of weathering. The crusts are generally fissured. Some fissures may also be found at greater depths especially in the intermediate zone between the dry crust

and the underlying clay. Here, too, the clays are nearly saturated. However, quick clays do not occur in the dry crusts.

DISTRIBUTION OF STRESSES IN THE NATURAL CLAYS

In a volume element of a saturated clay, the external load is supported by the forces in the solid phase corresponding to the stresses σ' and in the liquid phase by the water pressure u . If the clay has consolidated completely under the pressure of a certain maximum load, which is a time-consuming process, the clay is said to be "normally" consolidated for the stated load.

If the load is increased, the clay skeleton will be compressed (in the same manner as a sponge which is subjected to pressure) and since there is not sufficient time for the water to be expelled, the extra load is supported mainly by the excess water pressure. In cases where there are gases or fissures, the excess pressures will be less than those corresponding to the increased load.

The primary manifestation of the excess strain on the clay skeleton is a shear deformation of the clay elements with only a negligible change in the water content. At a shearing exertion, certain stresses—previously transmitted through the coarse grains that had become unlinked by the shearing, or through cementation bonds which have been broken—will in the quick clays be transferred to the clay and become apparent as an extra pore water pressure.

As a result of the water pressure gradients built up under load in this manner, flow of the water will occur until the clay skeleton in the solid phase is able to carry also the excess load via the contact pressures σ_{gr} between the coarser grains and via the interparticle forces σ_m in the clay matrix. The composition of the pore water and the sensitivity can also be changed.

Brenner has discussed whether the pore water pressure gradient can be completely dissipated or whether a threshold value would remain. On the basis of investigations carried out at SGI by Silfverberg (1949) and Hansbo (1960), it would appear that these phenomena met with in fine-grained clays are rather the results of variations in the permeability coefficient in Darcy's law at low pressure gradients.

The rigidity, however, is unevenly distributed within the skeleton, due among other things to variable distribution in elastic and plastic deformation properties. Due to this and to the effects of the above-mentioned shearing, a certain plastic effect will show up. This deformation process will continue, during a "secondary" consolidation, even after the "primary" (dependent on water pressure) consolidation period has reached its apparent conclusion (Osterman and Lindskog, 1963).

As a consequence of the plastic deformation, the clay becomes more

compact and thus stronger (Osterman, 1960a). Since the process takes place under the influence of external loads and almost constant pore water pressures, it seems quite reasonable to assume that a transfer of stresses, corresponding to stresses σ_c , occurs progressively as a result of chemical effects or of physical sliding effects, during the process. These stresses are supposed to be taken up in cementations and transferred to them from the above-mentioned weaker linkages. "Cementation" is here used to designate the observed strengthening of the interparticle linkages of unknown origin.

The total stress σ from an external load may thus be expressed as

$$\sigma = u + \sigma_{gr} + \sigma_m + \sigma_c$$

When the load is removed from a water-saturated soil element, its volume will show little increase. Since the external load is eliminated, a transfer of stress must take place in order to re-establish the balance. The grain pressure σ_{gr} will thus be reduced: the interparticle stress in the clay σ_m can be regarded as maintained apart from some minor adjustments due to remolding by the shear, and the stresses σ_c due to cementation can, for the most part, also be considered sustained. As a result of the above process, suction will arise in the pore water and the value of u will become radically altered; cf. Bishop and Henkel (1953).

It is apparent from the above that u can be composed of various parts which constitute reactions to uncompensated interparticle stresses. The osmotic effects will also exhibit reactions through the effect of the pore water pressure or other stresses. Mitchell (1962) and Ruiz (1962) have published interesting articles on the osmotic effects connected with this problem. When deciding whether the osmotic pressure can be read correctly on a given piezometer, consideration should be given to the principle of the pressure transfer and to the possibility of the formation of a semi-permeable filter of clay around the meter point.

STRUCTURE OF QUICK CLAYS AND CONDITIONS GOVERNING THEIR OCCURRENCE

The quickness of a clay is made possible by a certain constitutional instability of the structure of the undisturbed soil. In the following, an attempt is made to study the structure of quick soils and the conditions governing their occurrence from the point of view of a simplified theory.

A "true" quicksand may be built up as a loose lattice of grains of sand held together by small quantities of a kind of glue, usually consisting of cohesive material, Fig. 3. It may commonly be composed of clay, 1-3 per cent of the amount of sand. The filler material which might have previously existed in sufficient quantities, may now have diminished owing to water erosion or to chemical attack, until the structure has become unstable. As

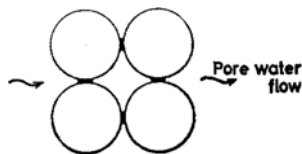


FIGURE 3.—Loose skeleton of coarse grains, cemented together by cohesive material and exposed to water flow and erosion, in principle.

a result of a small load or a vibration, the structure may collapse and the load will immediately become waterborne.

It can be assumed that, in principle, the process in quick clays is similar although somewhat more complicated. The clay structure consists of coarser, non-argillaceous grains surrounded by or embedded in the clay. Quick clays contain large quantities of water and it can be assumed that the excess water is rather loosely bound to the clay skeleton. The quick clay is therefore easily disturbed. According to the above, this arrangement should facilitate the uncoupling of the coarser grain skeleton during shearing and the transfer of part of the load to the water pressure.

In a clay mixture which is to be artificially converted (Söderblom, 1960) to a quick clay system, the incorporation of a quantity of coarser grains of non-argillaceous material, apart from the material in the clay fraction, has been found to contribute to the process and, in some cases, to be essential to it.

The present author offers the following hypotheses as possible explanations. During consolidation due to loading or to insufficient rigidity of the particle structure, compaction takes place and a tighter structure will be formed. Providing the clay consolidates at a moderate rate, similar to natural processes (during land uplift or other slow processes), both primary and secondary consolidations will occur. As mentioned earlier, this will give rise to a possibility of a more solid linkage by cementation. The further formation of a tighter structure may be prevented by the cementations.

If later a chemical change (dispersion) or internal erosion occurs and affects the magnitude of the interparticle forces, this need not reduce the total bearing capacity of the system, since the strength of the skeleton has been enhanced by the cementation. There will merely be a transference of stresses from one part of the solid phase to another. The result might be that the structure and interparticle intervals are more or less maintained.

On the other hand, a considerable change may occur in the water-binding ability. This means an increase of free water at constant water content. Under natural conditions, this process would require a considerable time, unless the chemicals influence a colloidal system that is already approach-

ing a critical stage. The quickness can then be interpreted as the opposite of coagulation—a kind of dispersion.

SIGNIFICANCE OF THE “UNDRAINED” SHEAR STRENGTH

In order to discuss the properties of quick clays, it is necessary to understand the importance of the “undrained” shear strength concept. The following simplified presentation of the problem will serve to illustrate the general ideas.

Let us imagine a box filled with loosely packed coarse grains surrounded by air and under stress due to vertical load. If the box is sheared, the grains will alter their positions, the volume of the system will be reduced—to an extent depending on grain shape etc.—and the load will settle. If, on the other hand, the coarse grains had a dense compaction, the volume would have increased and extra work would have been necessary in order to raise the load. At a given compaction, called the “critical density” (A. Casagrande, 1936), the volume will remain unchanged at shearing.

In the opinion of the present author, the value of the critical density is determined by minimizing the work performed to move the grains during shearing and which is essentially described by the scalar product of the friction stresses (from contact pressures) and their respective paths (regarded as vectors). The compaction relationships should therefore be theoretically determined on the basis of the “least work principle”.

If, in the case of the loosely packed grains, the box is filled with water and then sheared, the grain skeleton will also collapse but the total volume will remain unchanged, provided no drainage occurs (Fig. 4). The grain pressures, however, will disappear and the load will be supported by the water pressures. The shearing resistance τ which, in the foregoing case,

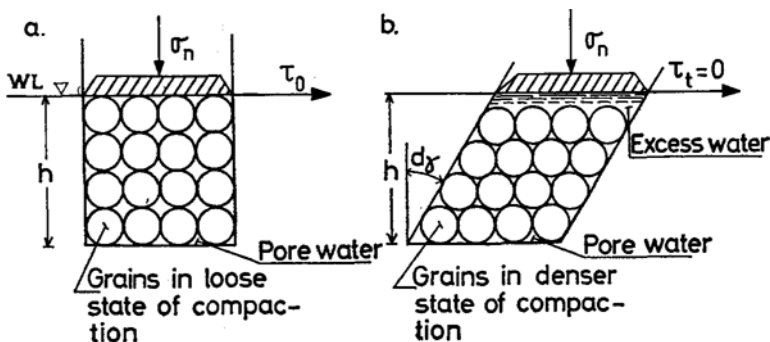


FIGURE 4.—Swayable box with loosely filled grains and water. Figure (a) shows the skeleton bearing the load σ_n before shearing, and figure (b) shows the off-loaded, contracted skeleton after shearing.

was dependent on the friction, will be almost zero. The “undrained shear strength” will therefore be low in a loosely packed, water-saturated material.

If the spaces between the grains are instead filled with pure clay, part of the grain pressures $\Delta\sigma_{gr}$ will during shearing be transferred to the clay (and taken up as pore water pressure Δu), Fig. 5. The undrained shear strength will then consist of the resistance of the clay, mainly due to interparticle stresses and also, where disturbance is moderate, to stresses in the cementations.

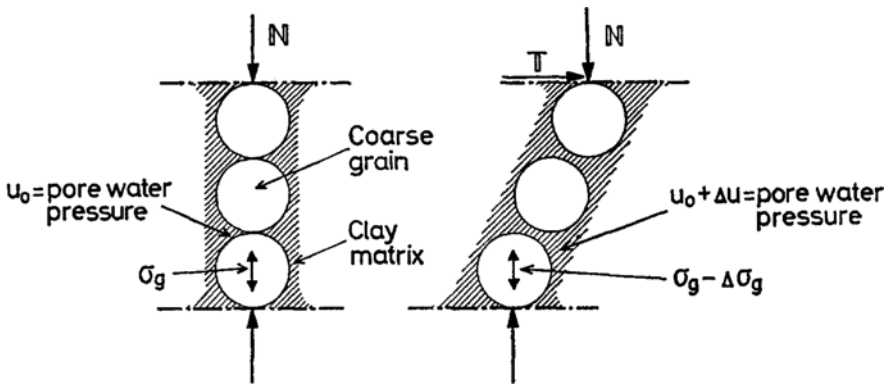


FIGURE 5.—Coarse grains carrying a load N and embedded in a clay matrix. The left-hand figure shows the original state before shearing, and the figure on the right a release of inter-granular contact after shearing. In the figure the stress transfer is, hypothetically, given to $\Delta\sigma_{gr}$ in the grains and to Δu in the clay pore water.

If, on the other hand, the compaction had been dense, shearing would have induced a tendency to raise the lid of the box (with a resultant tension in the pore water), causing an increase in the grain pressure and thus also in the friction resistance.

Thus, the “undrained” shear strength may be higher or lower than that of the “drained”.

The question of whether a stage representing a “critical” pore volume will also occur in clays—as proposed earlier by Hvorslev and Haefeli—has been taken up by Roscoe, Schofield and Wroth (1958). On the basis of experimental data, these authors found that the critical density is dependent on the load, the pore water volume and the shear stress. With these data as variables in a coordinate system, a unique spatial curve, “the critical void ratio line”, would exist towards which all load stages would converge. This lies below that void ratio which corresponds to “normal” consolidation, and a void ratio for “critical” overconsolidation should exist. In drained tests, specimens on the “wet” side of this value (line) will contract, or, in undrained tests, show positive pore water pressure changes; whereas

specimens on the "dry" side of the line show a tendency to dilate or, in undrained tests, to develop negative pore water pressure (suction).

The "undrained" shear strength of remolded clays τ_r is measured in soft clay by the fall-cone test (Swedish State Railways, Geotechn. Comm. 1922), see Karlsson (1961). This test involves a metal cone of a certain weight and a given angle being placed with the point touching the clay and then allowed to fall freely into the clay. The depth of penetration is measured. The Commission adopted as standard a cone of 60 grams weight and 60° apex angle. When this cone made an impression 10 mm deep, the clay was given a strength number of $H=10$. Other strength numbers were proportioned according to a cone weight capable of making a 10 mm impression. The number H_1 indicated remolded clay while H_3 indicated undisturbed clay. The quotient H_3/H_1 is often used as a measure of the sensitivity.

The undrained strength of remolded clays can also be determined in the laboratory by the use of the vane borer. This borer should be arranged so that it can be rotated at different speeds. When the speed is extremely low, a creep may occur even though stresses are moderate. At somewhat higher speeds, the resistance to the movement increases. The strength of the clay is increased due to removal of water (consolidation) and thixotropic phenomena (although to a successively less extent). At a certain intermediate speed the resistance may reach a minimum value which is used as a measure of the shear strength of the remolded clay. At higher speeds, there are greater increases in viscous resistance. If the resistance (on a linear scale) is plotted against the speed (on a logarithmic scale), a relationship is found which at moderately high speeds approaches a straight line. The cause of this is largely to be found in reduced interparticle stresses due to the increasingly marked parallel orientation (texture) of the particles. At the highest speeds, other changes occur which are of lesser interest in the present context.

The "undrained" shear strength τ_f in undisturbed clays can be measured *in situ*, e.g. by the use of a vane borer or a helical borer (Cadling and Odenstad, 1950; and Sökjer, 1961).

When the apparatus is pushed into the soil, it causes some disturbance, usually moderate. In sensitive clays, containing large quantities of coarse grains, this disturbance can cause a reduction in the strength. Root fibres and shells, etc., have, as a rule, the opposite effect. Further, the apparatus can give values which are too high because the effect of fissures is not registered. This is also true of soils which expand in volume during shearing, "dilatant" material, if the confinement is greater than in the actual problem. In the sensitive clays, however, the grain skeleton is generally contractant. As mentioned earlier, the results show a dependence on the test duration which consequently should be set at a definite value. (It may be mentioned that the test values should be reduced in practice, especially for clays with a high organic content, cf. Osterman, 1960b.)

It is also possible to determine the strength of extracted specimens. However, the sensitive soils can be disturbed by the sampling, by extraction, and in handling. To make the influence uniform there has been constructed a standard piston sampler (Swedish Committee on Piston Sampling, 1961), with plastic sample tubes in order to reduce chemical changes in the clay. Satisfactory specimens can also be obtained with a large-diameter sampler with metal foils (Kjellman, Kallstenius and Wager, 1950).

In testing the clays, it is possible to use also the simple unconfined compression test. In this case, the stress-strain diagram should be studied in order to observe whether the specimens have been disturbed. In the shear-box test (Jakobson, 1952) and the triaxial test the sensitivity can be reduced.

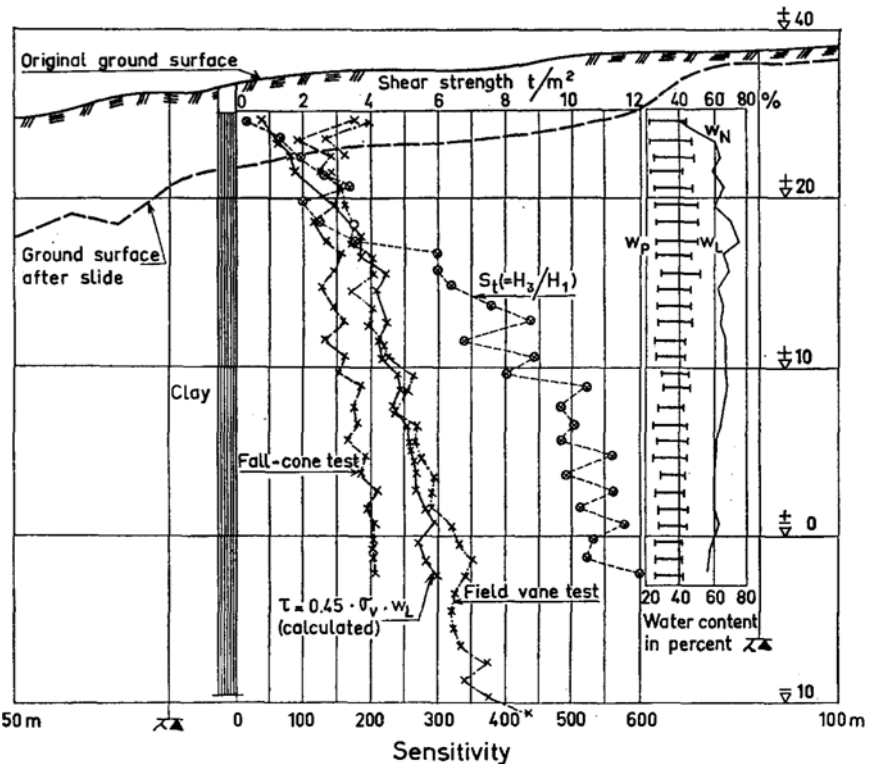


FIGURE 6.—Results of borings and laboratory tests from Section H 23.45 (included in a landslide) in the Göta River Valley and calculated strength values τ . In the plot the effective overburden pressure p is substituted for the effective vertical pressure σ_v . The borings have stopped at firm bottom, apparently rock. Liquid limit w_L , plastic limit w_p and natural water content w_N .

Figure 6 shows the strength τ_f determined by the vane borer *in situ* and by the fall-cone test. These samples were taken at various depths at a site in the Göta River Valley. The sensitivity values S_t are also included in the figure. Sensitivity is high, with values up to approximately 600. It can be seen from the figure that, in this case, the results of the fall cone test indicate lower values than the results of the vane test. The specimens were, however, taken with a small-diameter sampler and were therefore not entirely undisturbed.

RELATIONSHIP BETWEEN CLAY CONSISTENCIES

The consistency of a certain clay changes so that the strength decreases with increasing water content, cf. Fig. 7. This figure shows the shear strength for two remolded quick clays in kg/cm² (on logarithmic scale) according to the fall-cone test, as a function of the water content, expressed in per cent of the dry weight.

As is well known, Atterberg developed certain principles for the classification of consistency, e.g. the out-roll limit (plastic limit) w_p (lowest water

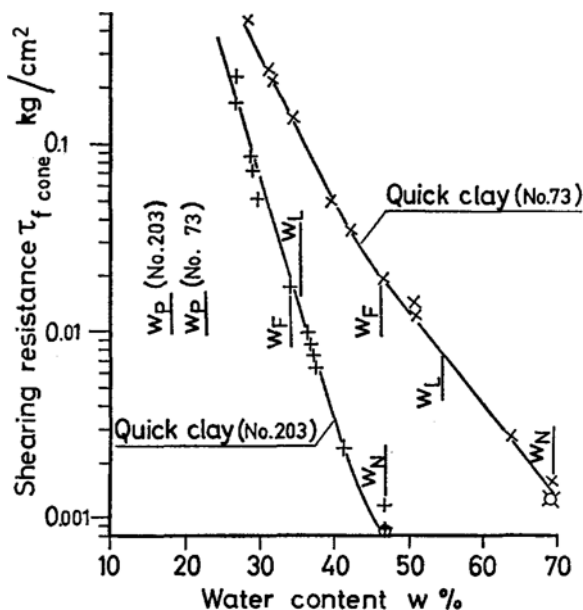


FIGURE 7.—Relation between shearing resistance τ_f (fall-cone tests) and water content w (per cent of dry weight) for two quick clays. As consistency characteristics there are given plastic limit w_p , liquid limit w_L , fineness number w_F as well as natural water content w_N .

content, in per cent of the dry weight, at which a clay specimen can be rolled out to a 3-mm thread) intended to mark the limit between "solid" and "plastic" clay, and the percussion liquid limit (liquid limit) w_L (water content, in per cent of the dry weight, at which the sides of a furrow in the clay will move together at percussion, cf. A. Casagrande, 1932 and 1958) which marks the limit between plastic and liquid clay.

The liquid limit, when determined by the fall-cone, is called the fineness number w_F (Swedish State Railways, Geotechn. Comm. 1922) at which the strength number $H_1=10$. This method appears to be more objective and is suitable for use on Swedish clays. A comparison between these two methods has been performed at SGI (Karlsson, 1961). "The shear strength" of remolded clay at the fineness number can be assumed to be between 0.015–0.020 kg/cm².

It has long been known that some kind of relationship exists between the undrained strength and the water-binding property of a clay. Olsson (1919) and Ekström (1927) reported the relationship between the shear strength and the fineness number. As the consolidation for a given load implies a strengthening of a clay until its solid phase is able to support the load, the strength is proportional to the effective load.

Skempton (1953), Hansbo (1957) and others have demonstrated certain relationships for the quotient between undrained shear strength τ_f and the consolidation pressure p_o (overburden pressure reduced by the uplift of water pressure) on the one hand, and the plasticity index I_p or the liquid limit on the other hand. Hansbo found that the formula $\tau_f=0.45 w_L p_o$ could be fitted rather well to vane test results from some common Swedish sedimentary clays. A similar relationship using I_p showed a somewhat wider scattering.

The shear strength, calculated in this manner, has been included in Fig. 6, from which it can be seen that in this case the quick clays behave as ordinary clays during vane borer tests *in situ*.

Figures 6 and 7 include both the consistency limits and the natural water content w_N . It can be seen from the figures that the natural water content exceeds the liquid limit in these quick clays. Actually this is by definition characteristic of the quick clays, namely that they can easily be transformed to a liquid state by disturbance.

In Fig. 8, the sensitivity of a total number of 1450 samples of marine clays, expressed as H_3/H_1 , has been plotted as a function of the quotient between the natural water content and the liquid limit. It will be noted from the figure that the sensitivity 30–50 corresponds to a natural water content of approximately 1–1.25 times the liquid limit. According to a compilation made by the present author, the same relationship, Fig. 9, appears also to apply to varved clays, usually deposited in fresh water during the glacial period.

The water content at which a remolded clay is flowing may thus be considered to agree roughly with the liquid limit. This limit is, however,

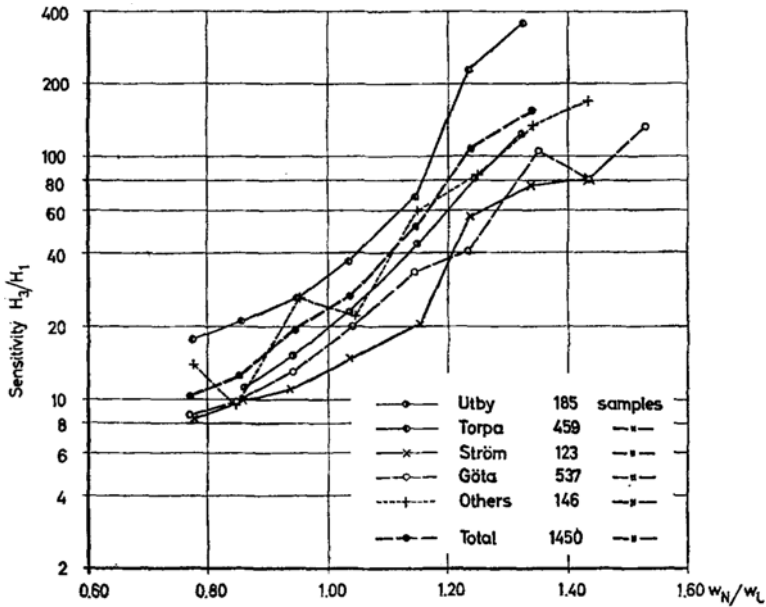


FIGURE 8.—Relation between sensitivity and the quotient between natural water content w_N and Atterberg limit w_L for a number of marine clays from the Göta River Valley.

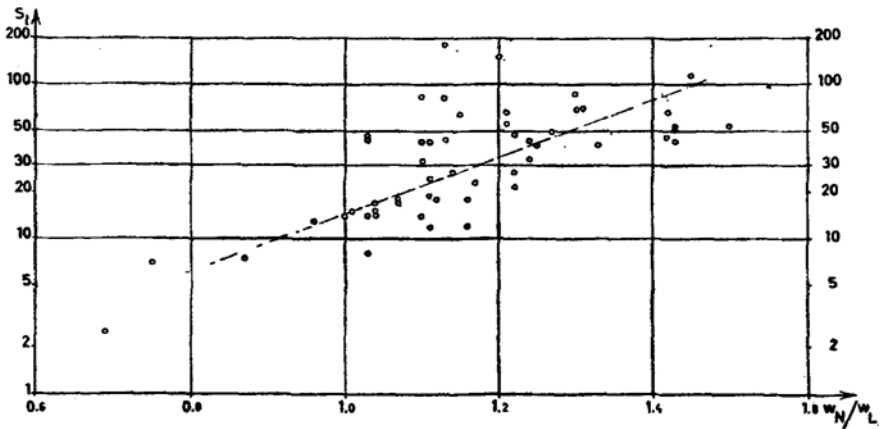


FIGURE 9.—Relation between sensitivity S_i and the quotient between natural water content w_N and liquid limit w_L (w_F) for a number of varved clays.

more on the dry side, especially in certain organic clays. Thus, w_N/w_L can be expressed by a mean value of approximately 1.15. Keinonen (1963) has shown that the relationship between the sensitivity and the excess water ($w_N - w_F$) differs for different fineness numbers.

If, in dealing with a remolded, salt-poor natural clay, the material is in a liquid state, it can in most cases be made more solid by adding certain electrolytes, such as sodium chloride. The main reason for this is a kind of coagulation effect similar to those of the clay suspensions, due to which a rather sparse clay skeleton may be formed. The hygroscopicity (Ekström, 1927), was increased in the tests when salt was added. The liquid limit is also high when there is a high content of non-decomposed organic materials, which bind large quantities of water.

STABILITY OF CLAY SUSPENSIONS

The stability of clay suspensions will be touched upon in the following, with regard to its importance in the understanding of the phenomena of quick clays.

As a rule, the mineral particles in a clay consist of crystalline systems in the form of simple sheets, or packets of sheets. The plain surfaces are generally negatively charged on the pure minerals. On the particles there thus exist uncompensated electrostatic charges from ions which exert an attraction on adjacent charges. In the literature there are presented some illustrations of the transfer of forces between the particles and the solution. However, recent literature has contained critical discussion of the details of the current theories, e.g. of the double layer theory in its common presentation, see Low (1959).

In the general textbooks, coagulation is according to the criticized theory treated as a result of a combination of electrostatic charges and temporary dipolar effects between the molecules or ions. This should give an alternating repulsion and attraction at different distances from the particles.

The present author feels, however, that the coagulation should be treated as a lability problem considering indirectly transferred influences rather than as an equilibrium problem. In order to achieve an effect similar to coagulation, a model was constructed consisting of two steel plates, magnetized crossways, Fig. 10. The simplified discussion illustrates two equal plates in opposite and parallel position.

Initially the plates are approached to each other giving an increase of repulsion. One of the plates is assumed for some reason to turn through a small virtual angle in relation to an axis or a point situated near the center of the plate. On the side where the plates approach one another the pressure will increase, as a function of the turn and the distance from the center of rotation. On the opposite side, the pressure will decrease. In this manner

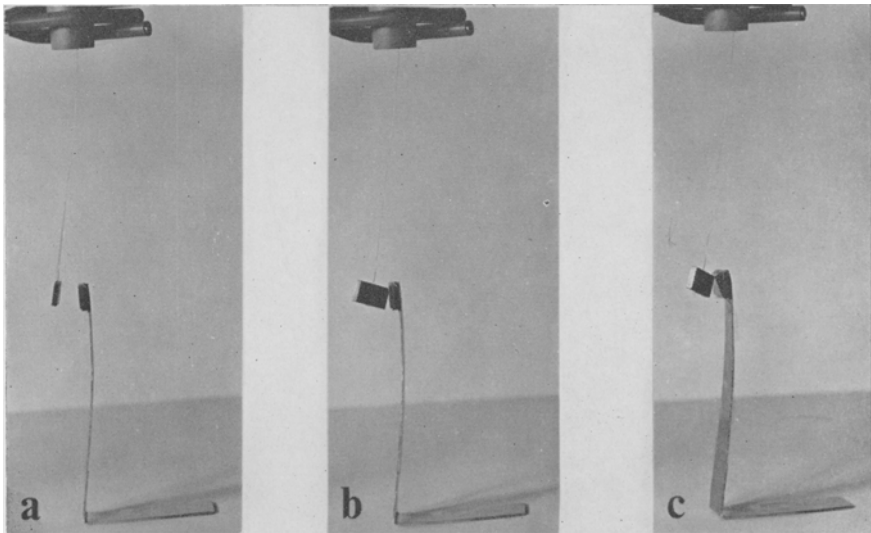


FIGURE 10.—Model of steel plates, magnetized crossways, intended to illustrate a mechanism of coagulation, in principle. Figure (a) shows the repulsion between the plates, having the same sign. Figure (b) shows the stability break-down because of polarization. Figure (c) shows the particle contact from another angle.

there is formed a retroverting reaction which is a function of the angular turn.

At the same time, however, the edge of the plate approaching the opposite plate will receive an opposite sign (charge) by polarization, and the other edge will likewise be influenced. The opposite plate will also become polarized. Due to this there will arise a forward directed rotary moment which is also a function of the angular turn (translatory movements should also be treated in an accurate study).

At a certain stage, depending on the circumstances, the energy of retroversion and of the forward rotary moment for a small change in angle may be equal. A minute change in the system, e.g. through the introduction of special influences, can thereby ensure the stability, or contrariwise, the instability of the plates. In the natural case the stress situation is more complex than in this simple model.

The above ideas are, however, introduced by the present author to provide an explanation for the sudden occurrence of coagulation and the formation of the rather porous structure of a coagulated clay which contributes to the concentration of water in the clay skeleton, and for the phenomenon of thixotropy. If so, particle size also has an influence. It is hoped also that it will stimulate further discussion on the subject.

PHYSICO-CHEMICAL CHANGES IN THE CLAYS

A couple of different theories exist concerning the physical and chemical changes likely to occur in the clays and which affect their sensitivity.

The scientist responsible for a pioneer contribution to this study is Rosenqvist (e.g. 1946 and 1955). On the basis of earlier investigations and his own observations he found that the quick clays in Norway have a very low salt content. He demonstrated that the sediment volume was strongly dependent on the salt content in the water phase. He further checked that the liquid limit rose, when sodium chloride was added, and he performed some experiments in which he produced a higher sensitivity in the clays investigated by means of leaching.

Ackerman (1948) reported that thixotropy is higher and the tendency towards flow lower in the fine clays as compared with coarse clays, and in the latter as compared with silty or fine sandy soils. In passing, he made an interesting observation in which he reported that blue clay under peat bogs becomes infiltrated with humic acids and the consistency of the clays is consequently deteriorated as a result of the water infiltration.

Bjerrum and Rosenqvist (1957) reported that experiments performed at a later date support earlier theories, e.g. that salt leaching in the pore water of a marine clay leads to an increased sensitivity and a reduced undrained shear strength. These authors also mentioned that the leaching was not accompanied by any extensive changes in the water content. The liquid limit showed a reduction during the experiments. The reduction

in shear strength due to leaching was assumed to be a result of the instability of the structure, leading to an increase in the pore water pressure at the time of collapse.

Certain investigations have also been performed by SGI on the physico-chemical reasons for the formation of quick clays. In order to test the theories concerning the effect of salt leaching, a probe was constructed by SGI (Söderblom, 1957) to determine the relative electrical resistance of the earth. Two electrodes were attached to the point of the probe. The point is connected to a tube which contains the leads from the electrodes. When the probe is put into the soil, the electrical resistance between the electrodes is measured. The electrical resistance is a function of the water content of the clay and of the amount of free electrolytes in the clay, cf. Sundberg (1932), Tölke (1937).

However, the results obtained from the measurements carried out by the Institute did not provide proof of any clear relationship between the electrical resistance and the quickness of the clay. Further, attempts made to produce quick clays by leaching certain natural salt clays were, in general, not successful.

A large number of quick clay deposits in fresh-water deposited clays have also been confirmed by SGI, particularly among stratified clays. The present author has studied profiles in which quick clays had been found at different levels and found that quickness could frequently be found in the vicinity of permeable layers. This might be explained by a combination of leaching and an absorption of chemicals.

The large landslide at Göta (1957), in the Göta River Valley, started with an initial small slide beside a ravine (through which there flows a brook) and at the river. In front of the slide there was a small quay and near it a sewer outlet. Subsequently, a number of secondary slides occurred in the rear regions and also upstream to the initial slide where quick clay deposits existed. Investigations carried out after the slide revealed that there had probably been an artesian water pressure in the earth under the slope. The water depth at the quay may also have undergone a change.

Further, there was a high content of impurities in the ground water, originating from industrial plants in the area. An engineer with experience from similar industries stated that slides in the neighborhood of sewers had occurred previously on a couple of occasions. The effect of the industrial impurities on the clay was therefore examined but the results obtained showed only a moderate effect.

The SGI laboratory then studied the effect of dispersing agents, e.g. sodium pyrophosphate (Söderblom, 1959), on natural clays. (Penner, 1963, has also performed similar tests.) Similarly, the occurrence of dispersing agents in nature was discussed, e.g. the possible effect of sodium silicate, alkaline sodium humate, sodium carbonate, etc. A clay deposit on Gärdet in Stockholm, which in all probability is fresh water deposited, was studied for impurities. The pore water contained among other things sodium and

magnesium. Special interest was paid to carbonates at that time, the reason being the risk of the inclusion of carbon dioxide in the water, derived from air. This might result during the prolonged leaching in the formation of quick clay. The investigations showed an effect of carbonate on the strength of a remolded clay.

In connection with these investigations, it was found to be possible to isolate a peptizing agent from a natural peat deposit of organic clay by treating it with sodium hydroxide solution. A dispersing agent such as this was found in a clay beneath the deposit. (The dispersing properties of humus have been discussed by Van Beneden, 1958.)

Several other areas were examined. In one of these, Rosshyttan, a stratified clay was found to lose its strength in alkaline treatment, Söderblom (1960). Jerbo confirmed that the clay was fresh-water deposited. A large section of the profile was found to lie within the relevant pH-range and to be quick. The greater part of its organic content obviously originated from the peat layers above it. The results of the tests on the action of alkali on the clay are given in Fig. 11. It can be seen that the diagram in the figure shows minimum in the shear strength of the remolded clay more or less within the region which, in other similar studies, was found to be most critical.

In addition to this, it can be noted that the ground water within some areas of Göta landslide, mentioned above, may have been affected by a

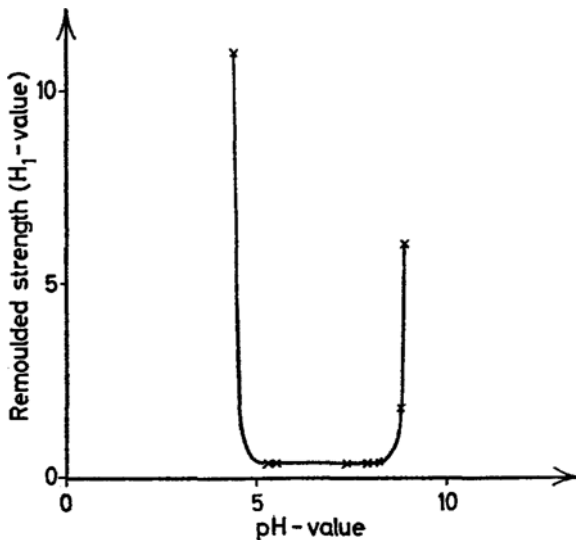


FIGURE 11.—Influence of sodium hydroxide treatment on the relative shear strength of a remolded clay from Rosshyttan plotted as a function of the pH-value.

brown, humus-rich water originating from a peat deposit. This water runs out in a site near to the secondary slides, occurring in the rear of the initial slide. The Swedish State Railways have recorded a large landslide at Kyrkviken in Kramfors, cf. Sandegren (1960), which started at a municipal dump and included great areas of the floor of the lake.

Specimens of natural clay, having a thickness of a couple of centimetres, were subjected to water dropping from a height of 10 cm for 24 hr. Tests were made with both clean and polluted water. In one case, it was mixed with 1 per cent sodium pyrophosphate and gave rise to a high degree of disaggregation, the clay subjected to the dropping becoming very quick. Another experiment involving combined leaching and peptizing may be mentioned. Glacial clay was dispersed in humus water from Rosenkälla. The suspension was poured into a solution of sodium chloride and the coagulating system permitted to precipitate. The cake of sediment was consolidated in a filter press and then leached with weakly alkaline water until the filtrate turned a brown color from the humus. The cake thus treated became quick. These two experiments signify (Söderblom, 1963) that water carrying dispersing agents, e.g. humus, can affect natural clays along the banks of waterways.

When the clay particles are transported along the waterway, they may be surrounded by a protective colloid (Holdridge, 1953), and be precipitated, e.g. when they meet salt water. A clay formed in this manner and subsequently leached may very well give rise to quick clay as a final product. The above experiments can be regarded as complementary to the leaching theory in relevant cases. In other cases, leaching is not necessary.

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