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EROSION OF COHESIVE SOILS

by

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S U M M A R Y

Erosion of a simple clay-water system is being studied. The micro-structure of two size fractions of the pure clay mineral used was examined by electron and optical microscopes as well as x-ray diffraction techniques. Results indicate that many accepted ideas of soil structure do not apply to the fractionated kaolinite used in this study.

Temperature and salinity of eroding water were treated as independent variables. A recirculating conduit was designed to permit control of these as well as of bed shear stress. The resistance of the kaolinite to erosion has been found to depend greatly on all these three variables.

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INTRODUCTION

In the study of loose boundary hydraulics, the emphasis has been placed on examination of the erosion and transport of cohesionless silts, sands and gravels. Materials of grain diameter greater than 0.1 mm are generally used, and gravity forces are clearly important. The combination of these resisting forces and the applied hydraulic forces leads to the movement of soil particles in a channel and a reshaping of the bed into a form which is dependent on the flow Froude number.

Cohesive soils are of much smaller grain diameter - a few μm and often less than 1 μm . Gravity forces are much less important here. Once a particle has been eroded, it will not deposit again until the flow is substantially reduced (9). The forces resisting erosion are particle surface forces and result from the arrangement of atoms and polar water molecules near the surface of the small particles. These forces are not as much dependent on the size of the particle as they are on chemical factors.

In order to throw some light on the influence of chemical factors on erosion of cohesive soils, it is necessary to concentrate initially on a simple clay-water system. The apparatus used must be chemically inert.

THE KAOLINITE PARTICLE

The particle is crystalline and the unit cell consists of a layer of silica bonded to a layer of alumina with most of the oxygen atoms in the alumina lattice replaced by hydroxyl groups. The surface of the particle is charged and the magnitude and sign of this charge can be altered by varying the acidity of water surrounding the particle. The charge on clay particles is considered to bring about an orientation of surrounding water molecules, thereby producing a more rigid water structure in the vicinity of the particle surface. This is believed to be the cause of plasticity in clays (3). Therefore, the pH of eroding water would be expected to be an important variable since it is one of the factors responsible for plasticity. It is possible that dumping of chemical waste into a once stable channel could have dramatic and costly consequences.

Particle charge can be reduced, in effect, by a screening process. This is brought about by increasing the concentration of salt ions surrounding the particle. Adding salt to a suspension of monodispersed particles consequently reduces mutual repulsion and allows the particles to approach each other to the point where van der Waals' attractive forces dominate and the particles cling together in a state known as flocculation.

In the present erosion studies, the pH is being kept constant at a value of 7. Screening of clay particle charge is being achieved by varying concentrations of neutral salts in the clay-water system.

Evidence has been found that the edges of kaolinite crystals are positively charged while their faces are negatively charged (6). It has been postulated that, in the flocculated state, unlike-charged crystal surfaces join and a "cardhouse" structure results. An open structure of this form explains the fluffy appearance of a deposited floc. Electron microscope studies have not confirmed the existence of the cardhouse structure. Sloan and Kell (11) found that kaolin fabric consisted of parallel and random arrangements of packets of flakes. They consequently suggested that the term "bookhouse" described the observed soil structure better than "cardhouse".

Single clay particles were examined using a transmission electron microscope and an optical microscope. The electron microscope gave a high resolution picture of the silhouette of a particle and indicated that the basic kaolinite particle was, in general, a stack of plates. Very few single hexagonal crystals were observed in this relatively coarse cohesive soil. It is possible to view only dried particles in the high vacuum necessary in an electron microscope. This can lead to uncertainties because of possible changes in structure due to recrystallisation of electrolyte. An aqueous suspension of particles can be viewed using an optical microscope. With this instrument, an oil immersion lens was found to give acceptable resolution at 1500 magnification. In this way, the "stack-of-platelet" structure of the individual particles was confirmed. Particles like this are probably responsible for Sloan and Kell's "bookhouse" structure. An electric field was produced by means of electrodes placed at both ends of the perspex box containing the suspension and the sign of charge on the particles was determined from their direction of migration. High concentrations of neutral salts (e.g. 1N NaCl) screened the particle charge completely and no migration took place.

Clays possess a capacity to exchange one type of ion for another and the more plastic a mineral, the higher its ion exchange capacity. Attempts have been made to relate ion exchange

capacity to particle charge and it has been considered as a variable in erosion studies (12). If a clay possesses a capacity to exchange cations which is higher than its anion exchange capacity, then the mineral should be negatively charged. But clay charge is pH-dependent whereas exchange capacity, while to some extent dependent on the nature of ions undergoing exchange, is nevertheless relatively constant and may be regarded as a property of the mineral. The clay under study has been found, using the optical microscope, to be positively charged in the water washed state and to possess a small cation exchange capacity but no anion exchange capacity. Therefore, particle charge is apparently unrelated to ion exchange capacity.

THE CONSOLIDATED CLAY

From considerations of screening of charge, it would be expected that a clay consolidated in salt water would be weakened if the salt was leached. Bjerrum and Rosenqvist (1) found this to be so. Their results give some evidence that a cardhouse structure exists in the quick clays investigated.

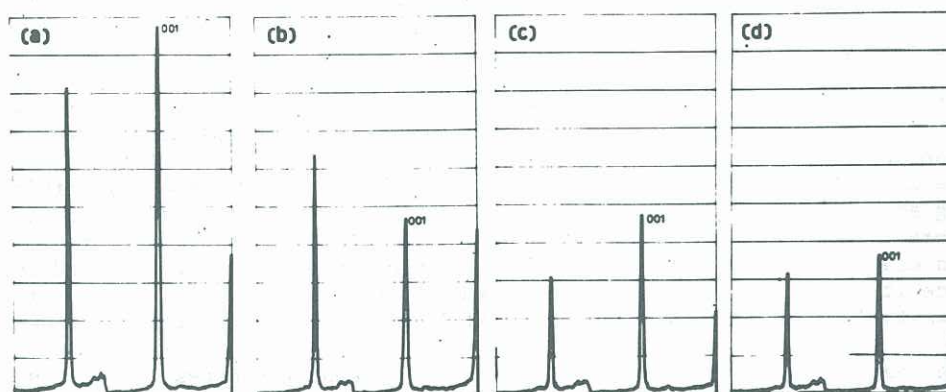


Fig. 1 X-ray Diffractometer Scans of Consolidated Kaolinite Size Fractions. (a) Deflocculated 2-5 μm ; (b) Flocculated 2-5 μm ; (c) Deflocculated 5-8 μm ; (d) Flocculated 5-8 μm .

The Georgia kaolinite used in the present erosion studies is dilatant and remoulds easily. Specimens are remoulded between periods of erosion to ensure the same starting conditions, that is a flat bed flush with the channel floor. It is conceivable that the apparent flow of soil particles that takes place on remoulding would cause a change in relative particle orientation. One preparation (the deflocculated fine size fraction) was examined before and after remoulding using an electron microscope. In both cases, the soil surface was found to consist of oriented platelets and no edge views of crystalline particles were apparent. Apparently, remoulding causes little change in the texture of this soil.

X-ray diffraction techniques were used to study the orientation of surface particles of the remoulded soil. The results of diffractometer scans are shown in Fig. 1. The indicated 001 peaks give a qualitative measure of degree of particle orientation. The deflocculated fine size fraction (Fig. 1(a)) is apparently highly oriented while flocculation is associated with increasing randomness of surface texture (Fig. 1(b)). For both the flocculated and deflocculated coarse size fractions the surface texture is much the same, as shown by similar 001 peak intensities in Fig. 1(c) and 1(d). However, the surface orientation indicated in Fig. 1(a) does not persist throughout the depth of the soil. Flat-plate transmission x-ray diffraction patterns indicated that there was no difference in orientation of particles throughout the bulk of the four specimens. These various x-ray techniques confirmed the findings using a scanning electron microscope where a relatively small population of particles is viewed.

EROSION APPARATUS AND TECHNIQUES

The bagged clay was deflocculated using a 0.4% by weight solution containing 33 parts of sodium hexametaphosphate and 7 parts of sodium carbonate. In this state, the two size fractions used were settled out. The deflocculating electrolyte was leached out by repeated washing of the size fractions in distilled water. The greater than $8\ \mu$ and the less than $2\ \mu$ size fractions were not used because they contain impurities. These size fractions were dried at room temperature and stored in polythene bags, and are referred to as water washed clay.

Specimens were prepared for erosion by consolidating into a perspex frame under a pressure of $30\ \text{lb f in}^{-2}$. Care was taken to ensure that the specimens remained saturated during consolidation - a latex membrane separated the slurry from the applied air pressure. This slurry was initially well above the liquid limit of the soil in order to ensure that consolidation of all specimens followed the virgin consolidation curve. The perspex frame forms the sides of a box and, after consolidation, a perspex floor was slid into place within these sides. The soil surface was then trimmed and the container of soil soaked for at least 4 hours in the same electrolyte in which it was consolidated. This time is the minimum necessary to age the soil before eroding (4). Early on in this aging period the soil was remoulded by tapping the sides of the container.

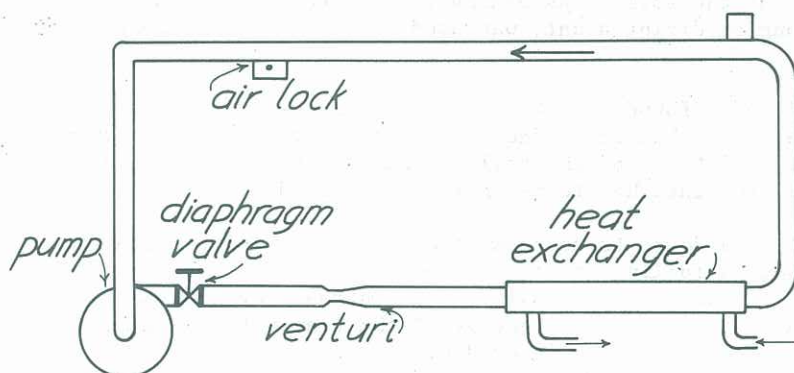


Fig. 2 Schematic View of Closed Conduit

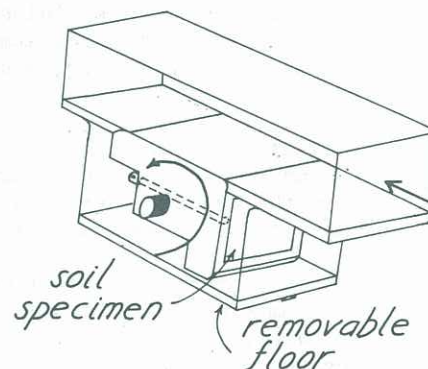


Fig. 3 Air lock in conduit

The channel in which erosion was carried out has a working section in the form of a 2 inch square closed conduit made of perspex. The return pipe is PVC and a stainless steel pump is used. Part of the return pipe is in the form of two coaxial stainless steel pipes. Cooling water is passed through the jacket to provide temperature control. The channel is a recirculating system and holds about 7 gallons of water. Distilled water was used with an addition of a known concentration of neutral salt as required. This water was then de-aerated by spraying into an evacuated glass carboy. De-aeration is necessary because bubbles form at high flows and these may effect results. A stock of the same de-aerated water is used for consolidation of the clay.

The layout of the conduit is depicted in Fig. 2. The box containing the soil specimen is inserted through an air lock (Fig. 3). This method of insertion means that the channel does not have to be drained every time the specimen is removed, and this increases the number of tests possible in a day. It also means that the water is retained within the insulating walls of the conduit and does not change temperature as readily as it would if removed. The water is brought to the desired temperature by circulating. If water at less than room temperature is required, chilled water is passed through the heat exchanger at the same time. For each test the elevation of soil surface of the specimen is jacked in between runs to make the surface flush with the channel floor.

At the end of a known period of erosion the specimen is removed and the loss of soil particles determined by weighing submerged in a beaker of the same electrolyte as in the conduit. Applied hydraulic shear stress is measured using Preston tubes and the results of Hsu (5). These tubes traverse the floor of the channel and retract into one side. They are attached to a micrometer and can be positioned to 0.001 in. Two such tubes are present, one upstream and one downstream of the specimen container. The Preston tube traverses showed that the shear across the channel was essentially uniform over the width of the sample box and the same upstream and downstream of it. Bed shear stress was determined as a function of the flow rate, measured by a venturi meter in the return pipe.

EROSION EXPERIMENTS

Initially, water washed clay was investigated. This was extremely weak, and would not stand in the vertical position. Accordingly, the air lock on the conduit could not be used and it was necessary to drain the channel between tests. The clay showed a surprising sensitivity to the temperature at which erosion took place. For example, 25°F rise in temperature was accompanied by a trebling of erosion rate at the same flow. The coarser fraction offered slightly more resistance to erosion, probably due to increased weight of the particles. In general the specimens behaved more like cohesionless material.

Attempts were made to use sodium chloride salt in the water. However, this caused corrosion in the welds of stainless steel components of the conduit and resulted in a strong time-dependence in erosion resistance of the soil. Accordingly, the steel was chemically passivated and sodium nitrate, a strong oxidizing agent, was used to salinate the eroding water thereafter.

Even minute concentrations of salt were found to make the soil much more resistant than in the water washed state. For example, less than one ounce of salt added to the seven gallons of water in the conduit increased the resistance of the soil so that for the same rate of erosion as with water washed soil the flow rate had to be increased tenfold.

Increasing concentrations of salt were found to decrease the sensitivity of the erosion process to temperature. In some cases, a falling off of erosion rate with increasing temperature was observed. This may be due to change of viscosity. An increase of erosion rate with increasing temperature may be attributed to the thermal energy of the clay water system and draws attention to the small size of the particles being eroded.

The clay particles themselves do not have an inherent vibration energy, but they are small enough to respond to the bombardment of surrounding water molecules which have a temperature-dependent kinetic energy. This is why clay particles in a suspension are seen to exhibit Brownian movement when viewed under the optical microscope. However, both of these effects are currently under study.

Unfortunately, it is not possible to use the same eroding shear stress for all salt concentrations. If the flow is too great the surface of the soil specimen becomes wavy with wavelength if the order of 1 in. and height up to 1/16 in. This approximately doubles the erosion rate as compared to a smooth surface under the same conditions. The mechanism for the formation of these waves is quite different from that in cohesionless soils; the process looks more like buckling of the surface layers. A stream of particles is carried into suspension from the whole of the leeward slope of these waves. Flows at which the bed erodes and remains smooth have to be found by trial and error. Whether or not to classify a bed as smooth is not always easy, because only visual observation can be used.

Because of these difficulties every experiment is repeated at least four times. The possibility of time-dependence is checked by eroding for different time intervals, the shortest being half a minute. In general the erosion rate has been found to be essentially independent of time.

The form of the shear stress versus erosion rate function at constant temperature is shown in Fig. 4. Observations indicate that stripping of particles does not take place over the whole bed area at low shear values while at the upper end, there is a strong tendency for the bed to buckle. Partheniades (8) is of the opinion that the term "critical shear stress" means little in cohesive soil erosion unless accompanied by corresponding erosion rates. He defined the critical value of shear as that shear stress at which there occurs a sudden increase of slope on the shear stress versus erosion rate curve. The critical value of shear in Fig. 4 is accordingly about 0.015 lbf/ft².

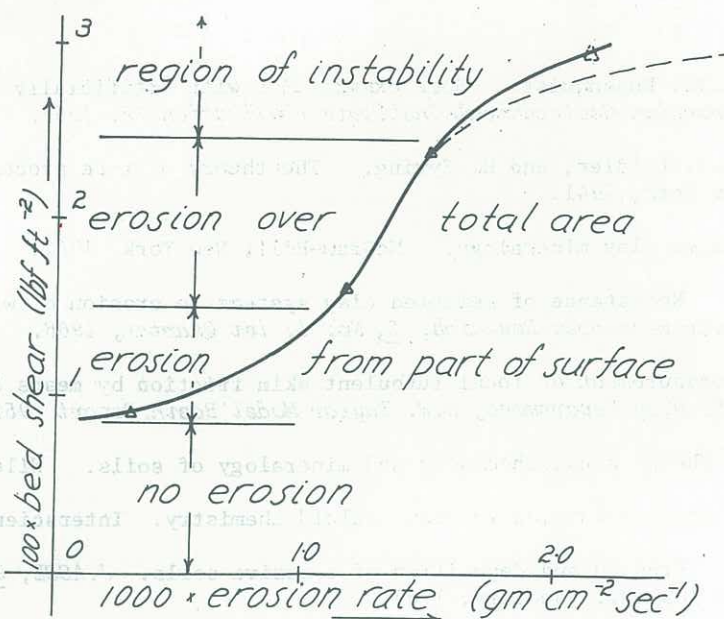


Fig. 4 Dependence of Erosion Rate on Bed Shear Stress for a 2-5 μm size fraction at 90 $^{\circ}\text{F}$ in 0.01N NaNO_3 .

The point indicated by a dashed triangle was obtained by halving the value of erosion rate obtained for a persistently buckling bed at a fluid shear of 0.031 lbf ft^{-2} . It is tentatively assumed that the full line gives the form that would apply to a smooth bed while the dashed curve shows what was actually observed as the bed became unstable.

CONCLUSION

From the trends reported in this paper it is seen that the problem of erosion of cohesive soils is as much a problem of chemistry as it is of hydraulics. In reported research on erosion to date, little attempt has been made to control chemical variables although reference is often made to their importance. It was decided to begin the present research by examining a pure clay mineral with a view to eventually considering controlled mixtures of minerals with addition of known quantities of cohesionless material. The complexity of the soil would be increased in stages until the mixture resembled that of natural soils and the water chemistry that of ground-water or river flow.

Although many research workers have attempted to correlate erosive behaviour with soil mechanics parameters, it must be realised that these are not primary variables (10) and that a complete break with soil mechanics description may be necessary. For example, critical shear stress appears to be unrelated to soil shear strength (8), suggesting that the stripping of particles at a soil-water interface is a rather different process from shear failure at a soil-soil interface.

The experimental program of erosion reported here is still in progress and it has been designed with the purpose of determining the applicability to soil erosion of (i) double layer colloid theory (7) and (ii) the rate process theory of reaction kinetics (2). Concentration of neutral salt is being varied to check the first theory and temperature in the second case. Results are still being obtained but indications are that both theories only hold over a limited range of conditions.

A simplified system permits the examination of the effect of primary or fundamental variables because it can be completely described in these terms. For example, a narrow size range of clay particles can be described by their mean diameter and their zeta potential (7) which gives a measure of charge carried by the particles. Although such a system is somewhat removed from a

natural soil-water system, investigations of such should ultimately lead to the establishing of soil erosion theory on a much firmer footing than is presently the case.

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