Factors influencing erosion in dispersive clays and methods of identification

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Abstract. Recent laboratory studies of the erosive behaviour of saturated cohesive soils using quantitative methods such as the rotating cylinder and flume apparatus showed that the mechanism of saturated cohesive soil erosion is basically a complex phenomenon involving the structure of the soil and the nature of the interaction between the pore and eroding fluids at the surface. In the case of partially saturated soils, erosion is further accelerated by a process called slaking. The slaking rate being influenced by the structure of the soil. Qualitative methods such as the dispersion ratio and the pinhole test are considered to be inadequate to evaluate the erosion potential and shear stresses of all soils. Relationships between critical shear stress, pore fluid composition and type and amount of clay characterized by the magnitude of dielectric dispersion or cation exchange capacity are presented for the prediction of erosion potential. In the case of dispersive clays the potential use of free swell tests as a method of evaluation is examined. It is considered that a gross quantitative evaluation of erosive behaviour can best be carried out using the rotating cylinder or a flume, using the loss in weight as a measure of erosion.

Facteurs influençant l’érosion par dispersion des argiles et méthodes d’indentification

Résumé. Des études récentes de laboratoire sur le comportement érosif de sols saturés et cohésifs à l’aide d’un cylindre rotatif ou d’un flume, ont montré que le mécanisme d’érosion de ces sols est un phénomène complexe qui fait entrer en ligne de compte la structure du sol et la nature de l’interaction entre la porosité et les fluides provoquant l’érosion de surface. Dans le cas de sols partiellement saturés, l’érosion est accélérée par un phénomène dénommé ‘slaking’, influencé par la structure du sol. Les méthodes quantitatives comme le rapport de dispersion ou le test ‘trou d’épingle’ semblent inadéquates pour évaluer le potentiel d’érosion ou les ‘shear stresses’ de tous les sols. La relation entre la ‘shear stress’ critique, la composition des fluides dans les pores et le type et la qualité de l’argile (indiqués par la valeur de la dispersion diélectrique ou la capacité d’échange en cations) est retenue pour permettre la prédiction de l’érosion potentielle. Dans les cas d’argiles sujettes à la dispersions, l’utilisation de tests d’accroissement libre de volume est prise en considération. Il est considéré que, pour une évaluation quantitative globale du comportement érosif, un cylindre rotatif ou un flume offrent les meilleures possibilités, en utilisant les pertes en poids pour mesurer le danger d’érosion.

INTRODUCTION

Problems of potential erosion are found in inland waterways, unprotected road cuts, drainage ditches, channels, embankments and other surfaces from which vegetation has been removed. The resulting erosion and waterborne sediment restrict the capacity of the drainage system and great amounts of water are lost by seepage and channel instability. Maintenance of navigable waterways, the control of inland water pollution, and the preservation of the balance of the aquatic ecosystem, all of which are affected by sediment circulation in inland waters, have been problems of great concern. Piping failures due to the dispersive nature of clays in small earth dams also have been reported from widespread localities in all states of Australia (Aitchison and Wood, 1965), USA (Sherard et al., 1972) and other parts of the world. Therefore a study of the factors influencing erosion and methods of evaluating erosion potential is necessary.

The purposes of this paper are to consider (a) the factors influencing erosion and dispersive clays and (b) methods of identification.
Factors influencing erosion

The phenomenon of erosion occurs when fluid flow-induced shearing stresses on a surface reach values great enough to cause particle removal from the surface. In erodibility criteria for noncohesive soils, the main resistance to erosion is provided by the submerged weight of the sediment, i.e. gravity forces. The mechanism of cohesive soil erosion is basically a complex phenomenon involving the structure of the soil and the nature of the interaction between the pore and eroding fluids at the surface. Recent laboratory studies of the erosive behaviour of consolidated soils using a rotating cylinder apparatus showed that the stress required to initiate erosion (critical shear stress \( \tau_c \)) is significantly affected by the amount and type of clay, pH, organic matter, temperature, water content, thixotropy and type and concentration of ions in the pore and eroding fluids (Alizadeh, 1974; Alizadeh and Arulanandan, 1976; Arulanandan et al., 1975 a, b; Sargunam, 1973). These studies have provided ample evidence to suggest that the structure of the soil and the osmotic influences set up at the surface of clay, due to the differences in the concentration gradients between the pore and eroding fluid, produce swelling of the clay surface. This swelling would reduce the interparticle bonding forces and thus would be a significant factor in the erosion of cohesive soils by water. The more dispersed the soil system is, the greater will be the swelling caused by the concentration gradients existing at a clay-water interface.

In the case of partially saturated soils, erosion may also be accelerated by a process called slaking. It is generally accepted that the slaking of partially saturated soil when in contact with water is due to excess air pressure in the capillaries that results from surface tension forces in the menisci. The entrapped air in the pores exerts pressures which are sufficient to break loose small bits of soil on the surface.

Slaking rate studies on compacted samples of a silty clay (Yolo Loam) (Kandiah and Arulanandan, 1974) indicate that the slaking is significant when samples are compacted on the dry side of optimum moisture content. The slaking rates decreased with increase in water content. The slaking rate was negligible at water contents greater than 5 per cent above the optimum water content for the compaction energy used in the study.

The study of the influence of mineralogy and pore fluid composition on the slaking rates of three silty clays containing 20 per cent kaolinite (Hydrite R), illite and montmorillonite at low and high SAR values, but at constant concentration of pore fluid (0.01N), showed that slaking rates are higher for the low plasticity and highly flocculated soil (Kandiah and Arulanandan, 1974). The soils with high concentrations of Na\(^+\) ions relative to Mg\(^{2+}\) and Ca\(^{2+}\) ions which are generally dispersed and possessing low permeability values showed a lower degree of slaking rate. It can be concluded from these observations that clay type and amount, pore fluid composition, water content, density and soil structure control the slaking rates of soils.

The above facts are sufficient to indicate that the mechanism of soil erosion is a complex phenomenon accelerated by the slaking process in the case of unsaturated soils.

Dispersive clays

The critical shear stress was determined by Shields (1936) as the value of the stress for zero sediment discharge obtained by extrapolating a graph of observed erosion rate versus shear stress as shown in Fig.1. Such a method does not depend on qualitative criteria. Using the concept of critical shear stress, a dispersive clay system will be defined as one with a critical shear stress, \( \tau_c \), equal to zero. This value of critical shear stress can be obtained either using a rotating cylinder or a flume as described subsequently.
Methods of quantifying pore and eroding fluid compositions and clay type and amount

In the last fifteen years, some researchers particularly in Australia and the USA, have shown that the dispersive nature of clay soil is strongly dependent on the pore and eroding fluid compositions and clay type and amount and can not be measured by the soil mechanics tests commonly employed by the civil engineer.

The type of the pore fluid is quantified by the relative amounts of the calcium, magnesium and sodium ions and expressed as the sodium adsorption ratio (SAR).

\[
\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{++} + \text{Mg}^{++}}{2}}}
\]

The concentration of salts in the pore fluid is expressed in normality. The composition of the eroding fluid can also be quantified by SAR and total salt concentration.

The combined effect of the type and amount of clay can be characterized by the magnitude of dielectric dispersion \(\Delta \varepsilon_0\) (Arulanandan et al., 1973). The value of \(\Delta \varepsilon_0\) is the difference in the dielectric constant measured at frequencies \(3 \times 10^6\) Hz and \(75 \times 10^6\) Hz. A proposed classification of clays using the parameter \(\Delta \varepsilon_0\) to characterize the type and amount of clay is discussed elsewhere (Arulanandan et al., 1973). The relationship between cation exchange capacity and \(\Delta \varepsilon_0\) is also discussed elsewhere (Fernando et al., 1976).

QUANTITATIVE METHODS FOR EVALUATING ERODIBILITY

A quantitative evaluation of the erodibility characteristics of soils has been obtained using two different devices: (a) a recirculating flume (Heinzen, 1976), and (b) a rotating cylinder apparatus (Arulanandan et al., 1975a).

Relationship between SAR, concentration, magnitude of dielectric dispersion and critical shear stress

A series of relationships between SAR, concentration, \(\Delta \varepsilon_0\) and \(\tau_c\) have been established (Alizadeh and Arulanandan, 1976) (Figs.2 and 3). The rotating cylinder apparatus was used to evaluate the value of \(\tau_c\). In general the results show that at concentrations of pore fluid greater than 0.05N and SAR values less than 20 the critical shear stress increases with increasing value of apparent dielectric dispersion or cation exchange.
At concentrations 0.005N the critical shear stress decreases with increasing magni-

capacity. At SAR values greater than 20 and concentrations greater than 0.05N the critical shear stress is independent of the amount and type of clay.

FIGURE 2. Relationship between critical shear stress and dielectric dispersion as a function of SAR. Pore fluid concentration 0.050N.

FIGURE 3. Relationship between critical shear stress and dielectric dispersion as a function of SAR. Pore fluid concentration 0.005N.
Factors influencing erosion in dispersive clays

The influence of low concentration of pore fluid on the erodibility characteristics is shown by the low values of $\tau_c (0-3)$ shown in Fig.3.

QUALITATIVE METHODS FOR EVALUATING ERODIBILITY

Qualitative tests such as the crumb test, the Soil Conservation Service dispersion ratio, and the pinhole test (Sherard et al., 1976) are generally used.

Crumb test (Emerson, 1967)
The test consists of dropping small samples at natural moisture content into a beaker of distilled water and observing the cloudiness. This test is very highly subjective and therefore will not be discussed further.

Dispersion ratio
The ‘dispersion test’ ($Dr$) is an indicator test developed by the Soil Conservation Service to evaluate the susceptibility of soils to erosion. In the ‘dispersion test’ the percentage of particles finer than 0.005 mm is measured using a method similar to the standard hydrometer analysis in which a soil water suspension is first prepared by breaking down the soil with a chemical dispersant and mechanical agitation. A second clay-water suspension is then prepared without using either dispersant or mechanical agitation. The degree of dispersion may be expressed by the ratio:

$$D = \frac{\text{per cent finer than 0.005 mm without chemical dispersant}}{\text{per cent finer than 0.005 mm without chemical dispersant}}$$

Pinhole test
The pinhole test, originally developed by Sherard et al. (1976) to evaluate piping erosion, is performed by causing water to flow through a small hole punched in the specimen. The water running through the specimens of dispersive soils becomes cloudy whereas the water running through erosion-resistant soils is crystal clear. Sherard classified the dispersive nature of soils under a flow caused by 50 mm head of distilled water. Intermediate soils erode slowly under 50 or 180 mm head of water, whereas nondispersive soils are supposed to produce no colloidal erosion under 380 or 1020 mm head of water.

Theoretically, shear stress can be calculated under laminar flow conditions if the diameter of the hole and the head producing water flow are known. The head which causes the flow emerging from the specimen to be visibly coloured with a colloidal cloud and does not clear with time can be used to calculate the critical shear stress.

Free swell tests
Clay soils generally expand in volume when they come into contact with water. In a saturated clay system, this process of swelling appears controlled by the ion concentration gradient and the net interparticle forces.

The familiar osmotic pressure concept has been found by Ladd (1960) to apply to clay systems since (a) there exists a concentration gradient between the electrolyte between the clay particles and the bulk ionic solution and (b) the electric field around the charged clay particles acts similarly to a semipermeable membrane. While the osmotic pressure gradient promotes swelling, the interparticle attraction opposes swelling. At equilibrium, denoted as constant water uptake for the type of swell tests used in this study, these opposing forces are balanced.

Free swell tests performed by McNeal and Coleman (1966), Arulanandan et al. (1975a), Alizadeh (1974), and Kandiah (1974) have all shown that for a given salt
concentration, an increase in SAR tends to increase water uptake and vice versa. Heinzen (1976) performed free swell tests on ten natural relatively undisturbed California soils including two which were highly dispersed. Heinzen found that the two dispersed soils swelled so severely that the soil pads lost all their original shape and turned to a liquid consistency. It was concluded that a dispersed soil loses all its cohesion due to swelling while a flocculated or aggregated system is more resistant to swelling.

Free swelling tests are performed using soil pads a few millimetres thick. These pads are saturated with pore fluid and then allowed to swell on sponges soaked with distilled water. The pads are weighed periodically until a constant weight has been reached. After a constant weight has been reached, the soil is dried and weighed.

DISCUSSION

Erodibility characteristics ($r_c$) obtained at the University of California, Davis from 1970 to date on various soils using the rotating cylinder and the flume and correlated with concentration, SAR and $\Delta e_0$ are compared with those obtained using the dispersion ratio, pinhole test, and the free swell tests.

The dispersion ratio cannot always be used to differentiate between highly erodible, and highly resistance to erosion. This may be due to the fact that the dispersion ratio is not an accurate method to evaluate all the complex factors affecting erosion. The dispersion ratio values obtained (Heinzen and Arulanandan, 1976) for dispersive clays ($r_c = 0$) appears to be greater than 70 for CL and CH soils and greater than 50 for ML, SM and SC soils. These values are somewhat greater than those originally proposed by the Soil Conservation Service and Sherard (Wahler and Arulanandan, 1976).

The pinhole test, like the dispersion ratio test used for the identification of dispersive clays, is an empirical test based on the subjective evaluation of the occurrence of dispersion. A recent study (Wahler and Arulanandan, 1976) using the ‘pinhole’ device to evaluate the erodibility characteristics of a highly erodible soil resulted in critical shear stresses of the order of hundreds of dynes/cm$^2$. These values are much too high. It is concluded that these abnormally high values are due to the nonuniform condition of the hole and partial clogging during the test. The ‘pin-hole test’ is also relatively insensitive since a head of only 1/2 cm is required to produce a shear stress in the order of 10—15 dynes/cm$^2$.

Free swell tests carried out on a large number of natural and artificial soils (Alizadeh, 1974; Alizadeh and Arulanandan, 1976; Arulanandan et al., 1975a; Heinzen, 1976; Kandiah, 1974) show that for highly dispersive soils the value of constant water uptake (osmotic swell) is a function of the type and amount of clay mineral. With the use of the magnitude of dielectric dispersion ($\Delta e_0$) to characterize the composition of the clays, a tentative relationship between constant water uptake and $\Delta e_0$ for soils with $r_c = 0$ is presented (Heinzen and Arulanandan, 1976). The use of $\Delta e_0$ to characterize the composition of clays was found to be necessary since different values of $\Delta e_0$ and $r_c$ have been obtained for soils with different mineralogy but having the same Atterberg limits (Sargunam, 1973). The relationship between constant water uptake and $\Delta e_0$ (Heinzen and Arulanandan, 1976) substantiated with additional results may provide a less subjective criteria for the prediction of dispersive soils.

CONCLUSIONS

(1) The phenomenon of erosion is a complex process between the structure of the soil and the composition of the eroding fluid. In unsaturated soil the process is further complicated by the slaking process.

(2) The dispersion ratio method cannot identify the erodibility nature of all soils.
(3) The pinhole test is an insensitive test and cannot be used to accurately evaluate the critical shear stress required to initiate erosion.

(4) From a physico-chemical point of view, the mechanism causing erosion has been shown to be due to osmotic swelling (Alizadeh, 1974; Arulanandan et al., 1975a). Since free swell is mainly due to osmotic swelling, the use of this test to identify dispersive clays appears to have merit.

(5) In cases where mineralogy and pore fluid composition are easily obtainable, charts shown in Figs. 2 and 3 may be used to evaluate erodibility characteristics.

(6) We believe that the rotating cylinder and flume test, using the loss in weight as a measure of erosion, provides accurate determinations of critical shear stress of core or remoulded specimens of cohesive soils.

REFERENCES


