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CHARACTERISTICS AND PROBLEMS OF DISPERSIVE CLAY SOILS

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16. ABSTRACT

The Bureau of Reclamation builds many structures of, on, in, and through earth materials, and clay soils are often used in construction because of their low permeability. In the past dispersive clay soils were not recognized, and failure of several structures built by other entities occurred before dispersive action was identified as a hazard to structures built of clay.

Dispersive clay soils are those with unique properties which under certain conditions deflocculate and are rapidly eroded and carried away by waterflow. For dispersive clay soils to erode, a concentrated leakage channel such as a crack (even a very small crack) must exist through an earth embankment. Erosion of the walls of the channel then occurs along the entire length at the same time. Unlike erosion in cohensionless soils, erosion in dispersive clay is not a result of seepage through the pores of a clay mass. Using dispersive clay soils in hydraulic structures, embankment dams, or other structures such as roadway embankments can cause serious engineering problems if these soils are not identified and used appropriately. This problem is worldwide, and structural failures attributed to dispersive clays have occurred in many countries. Much is now known about the presence, properties, and tests for identification of dispersive clays and for their use in civil engineering structures. The five tests most commonly used to identify these soils are described.

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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Using dispersive clay soils in hydraulic structures, embankment dams, or other structures such as roadway embankments can cause serious engineering problems if these soils are not identified and used appropriately. This problem is worldwide, and structural failures attributed to dispersive soils have occurred in many countries. Numerous investigations of these materials and their properties have been performed and are reported in international technical literature, as indicated in the Bibliography.

Because of the scope and size of potential problems which can occur with the use of dispersive clay soils, geotechnical engineers should be fully involved in the design of large earthfill dams and other civil engineering structures; however, experience shows that they have often not been involved in the design process. Recent design advances concerning the use of dispersive clay soils are not generally recognized.

Description of Dispersive Clay Soils

In the past, clay soils were considered to be highly resistant to erosion by flowing water; however, in the last few years we recognize that highly erodible clay soils exist in nature. Some natural clay soils disperse or deflocculate in the presence of relatively pure water and are, therefore, highly susceptible to erosion and piping. The tendency for dispersive erosion in a given soil depends on variables such as mineralogy and chemistry of the clay, as well as dissolved salts in the water in soil pores and in the eroding water (Sherard and Decker, 1977). Such clays are eroded rapidly by slow-moving water, even when compared to cohesionless fine sands and silts. When dispersive clay soil is immersed in water, the clay fraction behaves like single-grained particles; that is, the clay particles have a minimum of electrochemical attraction and fail to closely adhere to, or bond with, other soil particles. Thus, dispersive clay soil erodes in the presence of flowing water when individual clay platelets are split off and carried away. Such erosion may start in a drying crack, settlement crack, hydraulic fracture crack, or other channel of high permeability in a soil mass. The principal difference between dispersive clays and ordinary erosion-resistant clays appears to be the nature of the cations in the pore water of the clay mass. Dispersive clays have a preponderance of sodium cations, whereas ordinary clays have a preponderance of calcium, potassium, and magnesium cations in the pore water (Sherard et al., 1976a).

Dispersive clay phenomena were first noted by agronomists over 100 years ago and their basic nature was fairly well understood by soil scientists and agricultural engineers nearly 50 years ago (Richards, 1954; Volk, 1937), but the importance of the subject in civil engineering practice was not recognized until the early 1960's when research on piping failure in earth dams due to dispersive clay behavior was initiated in Australia because of many failures of small clay dams (Aitchison and Wood, 1965). Since that time, many investigations have been performed to refine procedures for identifying dispersive clays, because they cannot be identified by the conventional laboratory index tests such as visual classification, gradation, specific gravity, or Atterberg limits (Sherard et al., 1972a). Observations show there can be great differences in erodibility in materials with identical visual appearance and index properties when the samples are taken from locations only a few feet apart.

GEOGRAPHIC AND CLIMATIC FACTORS

Dispersive clays have not been definitively associated with any specific geologic origin but most have been found as alluvial clays in the form of slope wash, lake bed deposits, loess deposits, and flood plain deposits. In some areas, claystone and shales laid down as marine deposits have the same pore water salts as dispersive clay, and their residual soils are dispersive. In Zimbabwe dispersive clays have been associated with granites and sandstones as well (Clark, 1986).

In areas of sloping topography where dispersive clays exist, a characteristic pattern of surface erosion is evidenced by jagged, sinuous ridges and deep rapidly forming channels and tunnels. In gently rolling or flat areas there is frequently no surface evidence of dispersive clay due to an overlying protective layer of silty sand or topsoil from which the dispersive clay particles have been removed. The absence of surface erosion patterns typical of dispersive clays does not necessarily indicate that no dispersive clays are present. Dispersive clay soils can be red, brown, gray, yellow, or various combinations of these colors. Black soils with obviously high organic content are not dispersive (Steele, 1976). Nearly all fine-grained soils tested, known to be derived from in situ weathering of igneous and metamorphic rocks have been nondispersive, as well as all soils derived from limestone (Sherard and Decker, 1977).

Early studies indicated that dispersive clays were associated only with soils formed in arid or semiarid climates and in areas of alkaline soils. Recently the same soils and erosion problems have been found in humid climates in various geographic locations. Australia, Tasmania, Mexico, Trinidad, Vietnam, South Africa, Thailand, Israel, Ghana, Brazil, Venezuela, and many parts of the Southern United States have experienced problems with dispersive clays in water projects. Dispersive soils are found in 60 percent of Zimbabwe, and a embankment dam failure from dispersive soils was reported in Kenya (Clark, 1986).

ENGINEERING CONSEQUENCES

Most studies reported in the literature have shown that failures of structures built of dispersive clay soils occurred on first wetting. All failures were associated with the presence of water and cracking by shrinkage, differential settlement, or construction deficiencies. These failures emphasize the importance of early recognition and identification of dispersive clay soils; otherwise, the problems they cause can result in sudden, irreversible, and catastrophic failures.

Piping Failure Mechanism

Piping failure occurs in an earth embankment dam when a concentrated leak emerging at the downstream side is caused by water flowing through the pores of the soil. The erosion starts first at the discharge end of the leak, causing a local concentration of seepage and erosion forces. Erosion progresses upstream forming a tunnel-shaped passage or pipe until it reaches the water source, at which time a rapid catastrophic failure may result. Such erosion occurs mainly in cohesionless soils or soils with low cohesion which have little resistance to the plucking forces of seeping water.

With dispersive clay, piping is due to a deflocculation process where water travels through a concentrated leakage channel, such as a crack (even a very small crack), from its source. The erosion of the walls of the leakage channel then occurs along the entire length at the same time. Unlike erosion in cohesionless soils, erosion in dispersive clay is not a result of seepage through the pores of a clay mass. A concentrated leakage channel, even though it can be very small, must be present in order for erosion to start (Sherard and Decker, 1977). Erosion damage in embankments constructed with dispersive clays generally occurs in areas of high crack potential, such as along conduits, in areas of large differences in compressibility of foundation materials, or in areas of desiccation (Sherard et al., 1972a).

One of the properties controlling the susceptibility to dispersion piping is the percentage of adsorbed sodium cations within the clay particles relative to the quantities of other polyvalent cations (calcium, magnesium, and potassium). A second factor controlling susceptibility of a clay mass to dispersion piping is the total content of dissolved salts in the reservoir or canal water. The lower the content of dissolved salts in the reservoir or canal water, the greater the susceptibility of sodium saturated clay to dispersion.

When a concentrated leak starts through an embankment constructed of dispersive clay, either of two actions can occur (1) if the velocity is sufficiently low, the clay surrounding the flow channel can swell and progressively seal off the leak, or (2) if the initial velocity is high enough, the dispersed clay particles are carried away, enlarging the flow channel at a faster rate than it is closed by swelling, leading to progressive piping failure.

Rainfall Erosion of Dispersive Clay

There are several important differences in rainfall erosion potential of dispersive and nondispersive soil slopes.

Sheet or surface erosion by rainfall may occur in cohesive soil masses, often in conjunction with dispersive erosion. Slaking of soil grains contributes to the sheet erodibility of soil masses and may also be a factor in internal erodibility occurring in a dispersive clay soil when a dry surface is present for water contact within the soil mass. Reaction by the surface of the soil mass to water is essentially that of soil crumbs, and slaking is the breakup of soil crumbs into discrete fragments when immersed in water. This breakup may proceed to individual clay platelet size when the crumb particles are composed of dispersive clay. Two causes of slaking are replacement of entrapped air by water and internal shear stresses caused by swelling (Haliburton et al., 1975).

A study comparing laboratory behavior to field situations (Emerson, 1964) showed that when kaolinitic soil was wetted slowly from the surface, it did not slake to any depth, but when wetted quickly by a heavy rain it slaked to an appreciable depth. In the first case, vapor phase water entered the subsurface soil, allowing air to be dispersed. Water that was quickly introduced in liquid form caused slaking.

Another study (Huddleston and Lynch, 1975) described development of severe rill and tunnel erosion in nonvegetated cut and fill slopes of dispersive clay when there was heavy rainfall following a drought. Vegetated fill slopes of dispersive clay showed severe tunnel erosion under certain climatic conditions, i.e., heavy rainfall following a drought.

Natural slopes in nondispersive soils, normally covered with vegetation and containing organic matter in the topsoil in humid areas, usually exhibit little erosion. Dispersive soils are usually not present in the topsoil of natural slopes due to the process of eluviation, which is the movement of clay particles downward in the soil profile. One study of dispersive clays in the State of Mississippi showed that although severe rainfall erosion tunnels developed in many small dams, no rainfall damage was found in the undisturbed natural soil adjacent to the dams (Perry, 1979).

A relationship was developed between percent sodium and total soluble salts (same as total ionic concentration) in the soil pore water extract for earth embankments that were damaged by rainfall erosion (Sherard, 1972). Most of the earth dams and embankments that experienced rainfall erosion had excellent grass cover on the slopes. It was thought at the time (1972) that only embankments with soils containing less than 15 meq/L total soluble salts were susceptible to rainfall erosion. It has subsequently been shown that rainfall erosion occurs on compacted earthfills with total soluble salts in the range of 50 to 150 meq/L (Sherard and Decker, 1977; Bourdeaux and Imaizumi, 1975). It has also been noted that some soils classified dispersive by laboratory tests may not exhibit rainfall erosion on vegetated fill slopes or cut slopes any more severe than for nondispersive soils. This difference in dispersive clay behavior may be due to cracking potential, rate of swelling to close cracks, climatic conditions, or rate at which colloidal particles go into suspension (Sherard and Decker, 1977; Crouch, 1976).

Experiences with Dispersive Clay Soil

Because general recognition of dispersive clays in civil engineering practice is so recent, only a few major dams have been built since engineers have become aware of the problem; however, many other civil engineering structures have been built. Experience with thousands of earth embankment dams built according to current accepted practice has shown very few failures or problems from piping, and most of these failures/problems were attributable to some condition unforeseen by the designer, such as inadequate construction quality control or a geologic condition not discovered during explorations. Exceptions to the satisfactory performances were failures of homogeneous earth dams where leaks emerged on the downstream slope without having passed through filters. Many of these dams were relatively small and economically constructed, including farm pond dams built with minimal engineering attention (Sherard and Decker, 1977).

Most of the problems reported with dispersive clays occurred in existing earth embankment dams built before current identification methods and accepted design practices were in place. Problems that resulted were internal erosion or piping, tunneling, surface erosion, and jugging (formation of the vertical portion of an underground erosion tunnel where the base is larger than the top, resembling a jug).

Most studies cited in the literature have shown that failures of structures built of dispersive clay soils occurred on first wetting. These included cases where the reservoir or water level was raised after having been at a given elevation for a period of time. All failures were associated with the presence of water and cracking by shrinkage, differential settlement, or construction deficiencies (Haliburton et al., 1975; Perry, 1977; Perry, 1979; Sherard et al., 1972a; Sherard and Decker, 1977). Cracking has been determined to be a contributing factor since all structures that failed by internal erosion failed during first filling, and tunneling and jugging were often present without surface (sheet) erosion. Another condition for failure is that there must be a significant amount of material of a size which the initial flow of water could move to start the enlarging process. It has also been observed that vertical cracks in dispersive clay soils could enlarge by sloughing the upper walls into the lower reaches when water enters the crack, even though there was no flow through the crack (Steele, 1976). In addition to dispersive clay piping failure in homogeneous earth dams upon first filling of the reservoir, it is also possible for piping failure to occur at some later time if the ionic salts concentration of the reservoir water is substantially reduced. A case history of an Australian dam in an area of saline soil was presented (Ingles, 1964a) where the reservoir was originally filled with well water relatively high in ionic salts concentration, 26 meq/L, and the dam was stable for some years although continuous seepage losses were noted. Following completion of a 32-km pipeline to bring water from a river which had a lower ionic concentration (1.2 meq/L), the dam failed by piping within 3 days.

Several sites have been studied where only dispersive clay was available for the impervious section of a dam, and the abutments and foundation were of dispersive clay thick enough to preclude an economical seepage cutoff (Sherard and Decker, 1977). The studies showed that the risk of piping tunnels extending deep into saturated formations of dispersive clay below the depth of drying cracks or potential collapse on saturation was negligible and did not justify extensive protective design measures.

Only a few records (Sherard and Decker, 1977) exist of low dams in arid regions where piping tunnels passed through natural soil foundations or abutments a few feet below the bottom of the dam embankment, probably from leaks originating in drying or settlement cracks. Most earth embankment failures due to dispersive clays have been by erosion tunnels in the embankment itself, and there are no known cases of deep erosion tunnels in the foundation passing below the phreatic surface.

Knowing now that dispersive clays are found in widespread geographic areas, we can conclude that many small homogeneous earth embankments were constructed of dispersive clays because at the time they were considered good clay soils for earth dam construction. Many of these dams have performed well for a long time. The current practice for designing and building earth embankment dams and other water resources structures, including the use of well-designed filters and careful construction control, will result in safe dams and structures whether dispersive clay is used or not. However, the successful use of dispersive clays requires their recognition and identification and, when used in earth embankments, appropriate engineering measures must be taken.

Identification of Dispersive Clay Soils

Identification of dispersive soils should start with field reconnaissance investigations to determine if there are any surface indications such as unusual erosional patterns with tunnels and deep gullies, concurrent with excessive turbidity in any storage water. Areas of poor crop production and stunted vegetative growth may indicate highly saline soils, many of which are dispersive. However, dispersive soils can also occur in neutral or acidic soils and can support lush grass growth (Elges, 1985). Although surface evidence can give a strong indication of dispersive soils, lack of such evidence does not in itself preclude the presence of dispersive clay at depth and further explorations should proceed. Dispersive clays cannot be identified by the standard laboratory index tests such as visual classification, grain size analysis, specific gravity, or Atterberg limits and, therefore, other laboratory tests have been devised for this purpose. Clay soils should be routinely tested for dispersive characteristics during design studies for hydraulic structures where clay may be subjected to potential erosion and piping.

LABORATORY TESTS

The five laboratory tests most generally performed to identify dispersive clays are the crumb test, the double hydrometer test, the pinhole test, the test of dissolved salts in the pore water, and the ESP (exchangeable sodium percentage) based tests. The first four tests are most commonly used in the United States and the fifth test is the one most common and reliable in Australia (Aitchison and Wood, 1965; Eagles, 1978; Murley and Reilly, 1977; Rallings, 1966; Stone, 1977), South Africa (Elges, 1985), and Zimbabwe (Clark, 1986). It is important that all soil specimens be maintained and tested at their natural water content since drying, especially ovendrying, may alter dispersive characteristics (Acciardi, 1984; Sherard et al., 1976a; Sherard and Decker, 1977). While the several tests give consistent results for many soils, there are a significant number of exceptions. Consequently, it is prudent to perform all five tests on each soil sample.

The Crumb Test

The Emerson Crumb Test (Emerson, 1967) was developed as a simple procedure to identify dispersive soil behavior in the field, but is now often used in the laboratory as well. The test consists of either preparing a cubical specimen of about 15 mm on a side at natural water content or selecting a soil crumb at natural water content of about equal volume. The specimen is carefully placed in about 250 mL of distilled water. As the soil crumb begins to hydrate, the tendency for colloidal-sized particles to deflocculate and go into suspension is observed. Results are interpreted at timed intervals and four grades of reaction are discernible: 1 - no reaction; 2 - slight reaction; 3 - moderate reaction; and 4 - strong reaction (colloidal cloud covering the entire bottom of the container).

The following interpretive guide may be used to assess dispersive potential:

- No reaction: The crumb may slake and run out on the bottom of the beaker in a flat pile but there is no sign of cloudy water caused by colloids in suspension.

- Slight to moderate reaction: There is a bare hint to easily recognizable cloud of colloids in suspension. The colloids may be just at the surface of the crumb or spreading out in thin streaks on the bottom of the beaker.

- Strong reaction: The colloid cloud covers nearly the entire bottom of the beaker, usually in a very thin layer. In extreme cases, all the water in the beaker becomes cloudy.

The crumb test gives a good indication of the potential erodibility of clay soils, however, a dispersive soil may sometimes give a nondispersive reaction in the crumb test. If the crumb test indicates dispersion, the soil is most likely dispersive. The test procedure is fully described in USBR 5400, Procedure for Determining Dispersibility of Clayey Soils by the Crumb Test Method (Bureau of Reclamation, 1990).

The Double Hydrometer Test

The SCS (Soil Conservation Service) laboratory dispersion test, also known as the double hydrometer test, is one of the first methods developed to assess dispersion of clay soils. The current test method was developed in 1937 from a procedure proposed by Volk (1937).

The sample should be shipped to the laboratory in an airtight container to prevent moisture loss. Testing is performed on specimens at natural water content.

The particle size distribution is first determined using the standard hydrometer test in which the soil specimen is dispersed in distilled water with strong mechanical agitation and a chemical dispersant. A parallel hydrometer test is then made on a duplicate soil specimen, but without mechanical agitation and without a chemical dispersant. The "percent dispersion" is the ratio of the dry mass of particles smaller than 0.005-mm diameter of the second test to the first expressed as a percentage as shown on figure 1. Procedures for performing the test are outlined in USBR 5405, Determining Dispersibility of Clayey Soils by the Double Hydrometer Test Method (Bureau of Reclamation, 1990; Kinney, 1979).

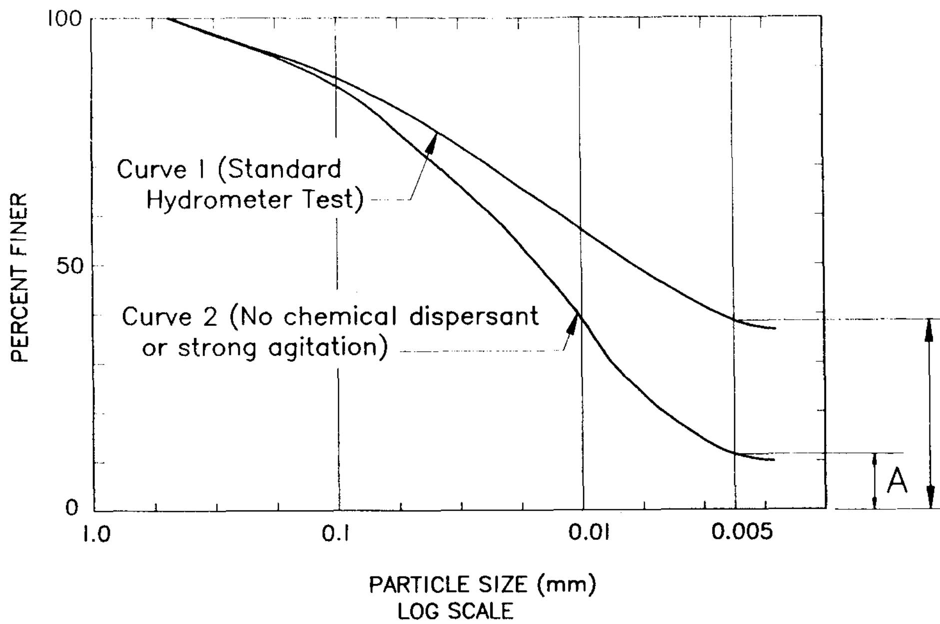
Criteria for evaluating degree of dispersion using results from the double hydrometer test are:

Percent dispersion	Degree of dispersion
<30	Nondispersive
30 to 50	Intermediate
>50	Dispersive

Numerous tests should be performed because soil dispersiveness can vary greatly over short distances within a borrow area, along a canal alignment, or within an existing embankment. Test results show that a high percentage of soils with dispersive characteristics, exhibited 30 percent or more dispersion when tested by this method (Sherard and Decker, 1977).

The Pinhole Test

The pinhole test was developed to directly measure dispersibility of compacted fine-grained soils in which water is made to flow through a small hole in a soil specimen, where waterflow through the pinhole simulates waterflow through a crack or other concentrated leakage channel in the impervious core of a

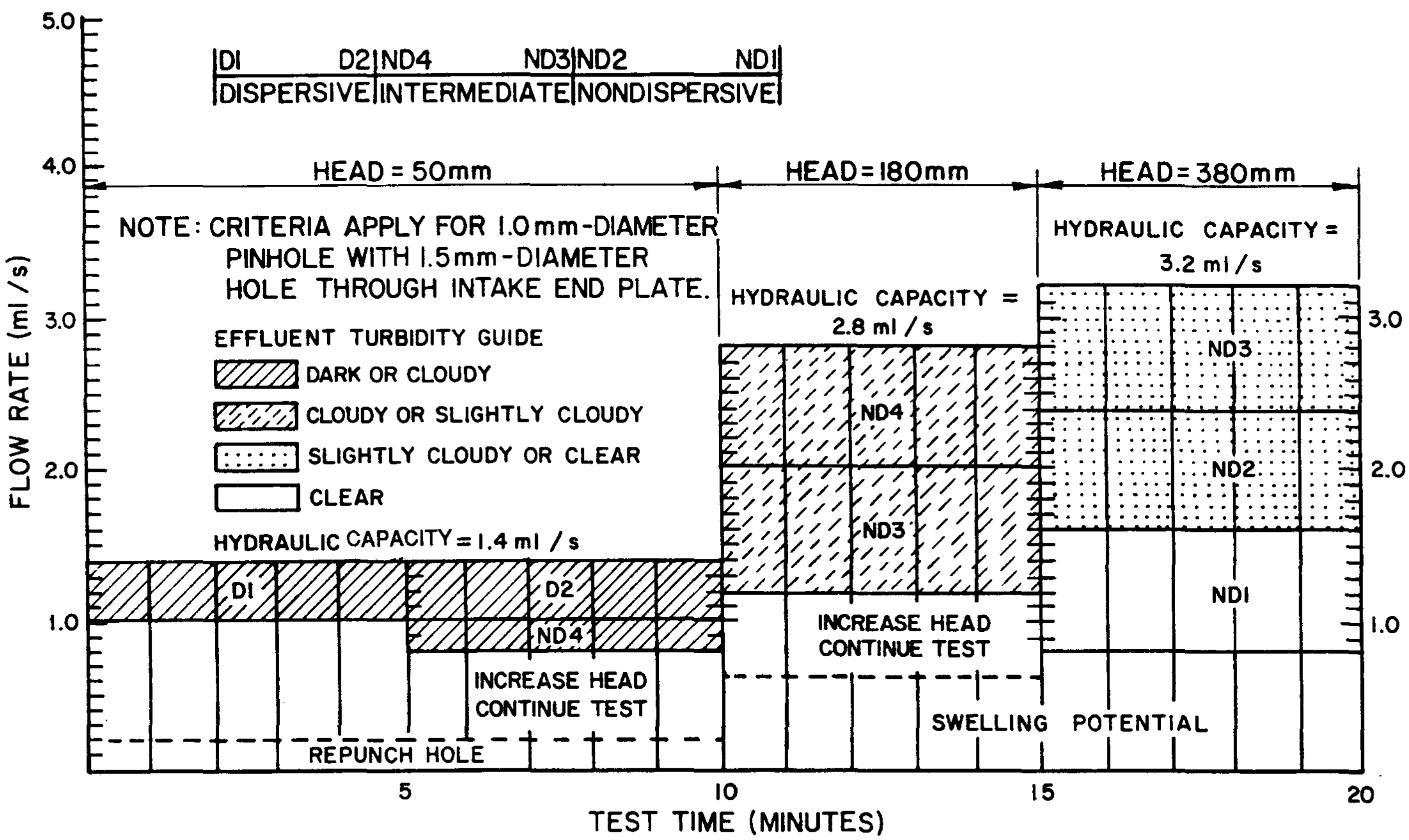


DEFINITION: PERCENT DISPERSION $= \frac{A}{B}(100)$

Figure 1. - Percent dispersion as determined from the double hydrometer test.

dam or other structure. A 1.0-mm-diameter hole is punched or drilled through a 25-mm-long by 35-mm-diameter cylindrical soil specimen. Distilled water is percolated through the pinhole under heads of 50, 180, and 380 mm (hydraulic gradients of approximately 2, 7, and 15), and the flow rate and effluent turbidity are recorded. The 50-, 180-, and 380-mm heads result in flow velocities ranging from approximately 30 to 160 cm/s at hydraulic gradients ranging from approximately 2 to 15. The test was developed by Sherard et al. (1976a) and in the past few years has become a widely used physical test (Acciardi, 1984; Craft, 1984; Craft and Acciardi, 1984). It is important that the test be made on soil at its natural water content because drying may affect test results for some soils. If the material contains coarse sand or gravel particles, these should be removed by working the sample through a 2-mm sieve (U.S. Standard No. 10). The natural water content should be determined and the desired water content for compaction achieved by adding the required amount of water (or by gradually air-drying, if too wet). All water added should be distilled water. Detailed test procedures are outlined in USBR 5410, Determining Dispersibility of Clayey Soils by the Pinhole Test Method (Bureau of Reclamation, 1990).

As a result of extensive laboratory investigations and a field testing program completed in 1982, Reclamation modified the original pinhole test procedure and equipment. The modified pinhole test produces the same result as the original test, but with improved specimen preparation, handling, control, and testing consistency. A quantitative method of identifying the different grades of dispersibility was also developed as shown on figure 2 (Acciardi, 1984).



DISPERSIVE GRADE VS FLOW RATE

SAMPLE NUMBER	PLACEMENT CONDITIONS		DISPERSIVE GRADE CLASSIFICATION
	DRY DENSITY	MOISTURE CONTENT	

Figure 2. - Dispersive grade vs. flow rate from the pinhole test.

Other indirect tests such as the crumb test, double hydrometer, and soil pore water cation and zeta potential analyses are also used to help identify dispersive clays. However, results from the individual tests often do not agree, and the pinhole test is considered the most reliable since it is a direct physical test. It is emphasized that all of the tests should be performed on each soil sample for the most complete information and most reliable identification.

Chemical Tests

During the 1960's Australian researchers recognized the presence of exchangeable sodium as a main contributing chemical factor to dispersive clay behavior (Aitchison and Wood, 1965; Ingles and Wood, 1964a; Rallings, 1966). The basic parameter to quantify this effect is ESP (exchangeable sodium percentage), where:

$$ESP = \frac{exchangeable\ sodium}{CEC\ (cation\ exchange\ capacity)} \times 100$$

Soils with ESP of 10 or above which are subject to having free salts leached by seepage or relatively pure water are classified as dispersive.

Criteria which have been used to classify dispersive clays using ESP data are:

ESP	Degree of dispersion
<7	Nondispersive
7 to 10	Intermediate
>10	Dispersive

Another parameter commonly evaluated to quantify the role of sodium with respect to dispersion when free salts are present is the SAR (sodium absorption ratio) of the pore water where:

$$SAR = \frac{Na}{0.5\ (Ca + Mg)} \quad with\ units\ of\ meq/L$$

The SAR method is not applicable if no free salts are present. Use of the SAR is based on the fact that soils in nature are in equilibrium with their environment. In particular there is a relationship between electrolyte concentration of the soil pore water and the exchangeable ions in the clay adsorbed layer.

Australian researchers showed that all soils were dispersive if SAR exceeded 2. This shows reasonable agreement for soils with TDS (total dissolved salts) between 0.5 and 3 meq/L but not for soils outside this range as shown on figure 3 (Clark, 1986). The currently accepted method of evaluating the chemical influence on dispersive behavior in the USA is shown on figure 4 where:

$$Percent\ sodium = \frac{Na\ (100)}{TDS} \quad with\ TDS = Na + Ca + Mg + K$$

and all units in meq/L of saturation extract.

To obtain saturation extract, soil is mixed with distilled water until a saturated soil paste with water content near the Atterberg liquid limit is obtained. The paste is allowed to set for a number of hours until equilibrium is attained between the salts in the pore water and those on the cation exchange complex. Subsequently, a small quantity of pore water is filtered from the soil paste using a vacuum. This extracted pore water is tested using routine chemical tests to determine the amounts of the main metallic cations; calcium, magnesium, sodium, and potassium, in terms of milliequivalents per liter. The percent sodium and TDS (sum of the four metallic cations) are determined. The chemical tests are performed using procedures established in the United States Department of Agriculture publication, Diagnosis and Improvement of Saline and Alkali Soils (also known as Handbook 60) (Richards, 1954). Handbook 60 was issued in February 1954 and was reviewed and approved for reprinting in August 1969.

Although figure 4 has been used with some success in the United States, statistical analyses of data have shown that the method does not agree with physical test (pinhole) results for five of six groups of soils investigated (Craft and Acciardi, 1984). The use of figure 4 has been successful where preliminary data show soils from a given area demonstrate a good correlation between the chart on the figure and the pinhole test. Further use of the chemical test can then be carried out on soils from the same area with some confidence when pore-water data are used in conjunction with physical tests. It has been recommended that the pore-water discriminating variables be evaluated for each site using a discriminant analysis procedure (Craft and Acciardi, 1984). This will allow selection of the most successful combinations of variables for the particular job.

Figure 4 was not reliable for soils tested in South Africa and Zimbabwe (Clark, 1986); therefore, a procedure was developed for evaluating effects of dissolved salts in the pore water on dispersive potential as shown on figure 5 (Elges, 1985). To date, this procedure has not been widely used in the United States and no correlative studies have been performed. The primary requirement for taking soil samples in the field for any method of dispersive testing whether in the United States or elsewhere is to ensure that there is no moisture loss from the sample. Samples should be shipped to the laboratory in airtight containers.

ENGINEERING CONSIDERATIONS

In many failures of earth embankments caused by dispersive clays, failure of the embankment was the first indication of the existence of dispersive clays in the area. These situations point up the importance of early recognition and identification of dispersive clay soils. The problems they cause can result in sudden, irreversible, and catastrophic courses of events leading to failure or near failure. To avoid later serious problems and to properly utilize available earth construction materials, the possible existence of dispersive soils should be considered in the earliest investigation stages. This is especially true where the geologic and surface evidence described earlier exist. When dispersive soils are found during the materials exploration phase, decisions can be made to look for alternate materials or proceed with necessary engineering provisions to deal with the dispersive properties.

Selection of Materials for Economic Construction

Although dispersive soils require special provisions when used in earth embankments, these materials may represent the most economic choice of materials for a specific situation. Concern for the limitations of these materials and the serious problems they may cause should not be reason to avoid their use where alternate materials would be more expensive.

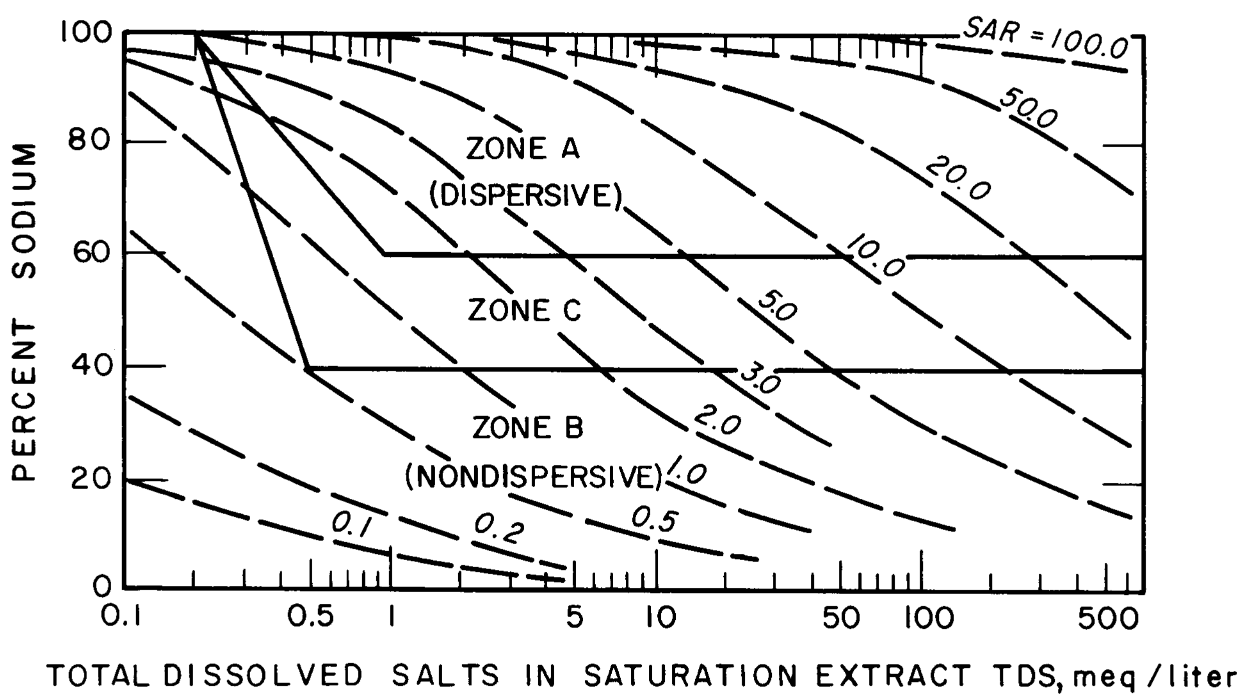


Figure 3. - SAR superimposed on TDS chart.

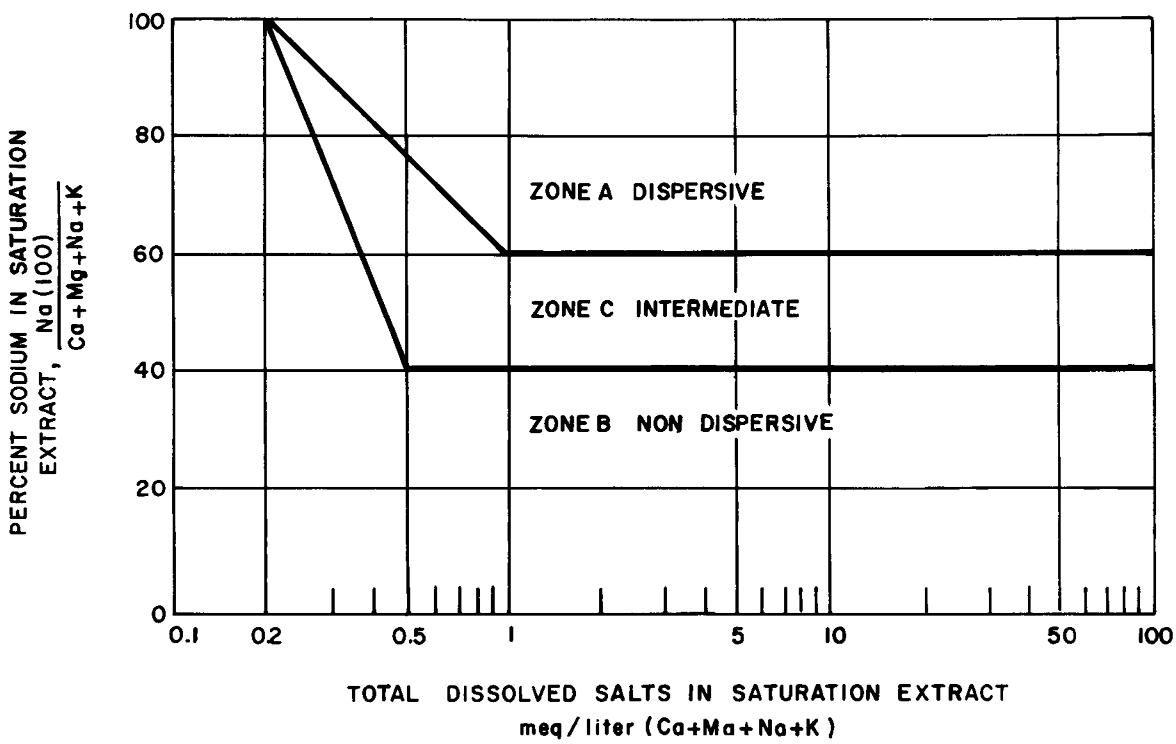


Figure 4. - Dispersive potential vs. TDS.

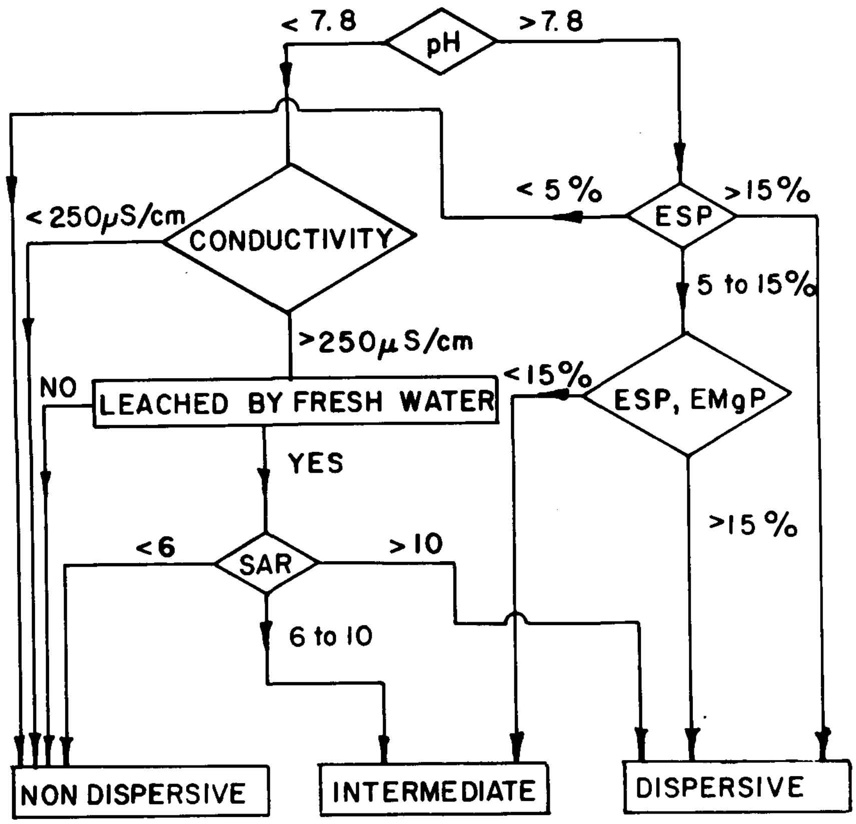


Figure 5. - Dispersive potential evaluated from analysis of dissolved salts in pore water.

Design and Construction Measures

Almost all of the considerable number of failures due to dispersive clay have occurred in homogeneous earth embankments without filters and all piping failures were caused by an initial concentrated seepage path through the embankment. Seepage paths through embankments can be caused by cracking due to desiccation, differential settlement, saturation settlement, or hydraulic fracturing.

Additionally, areas of potentially high soil permeability such as around conduits through the embankment, concrete structures, and at the foundation interface all require special treatment and attention during construction. If piping due to deflocculation is to be avoided, permeability should be less than 10^{-5} cm/s. Careful control of compaction and water content during construction are thus necessary to minimize these conditions.

Sand filters can effectively and safely control leaks in embankments whether they are constructed of dispersive or nondispersive clay. In sealing and filtering a leak in dispersive clay the filter cannot stop the colloidal particles in suspension from passing through, but the silt-size particles carried by the flow cannot enter the sand filter and are retained in the leakage channel upstream of the filter, and gradually seal the leak. With nondispersive soils the filter is designed to prevent all fine particles from a protected zone from entering the filter.

Based on the above, Sherard et al. (1984b) state that sand or gravelly sand filters with $D_{15} = 0.5$ mm or smaller will safely control and seal concentrated leaks through most dispersive clays with d_{85} larger than about 0.03 mm. Sand filters with $D_{15} = 0.2$ mm or smaller are conservative for the very finest dispersive clays. For clays having similar particle size distribution, whether dispersive or nondispersive, the required filters are the same.

where:

D_{15} = particle size in the filter of which 15 percent are smaller, by dry mass of soil
d_{85} = particle size of the base soil of which 85 percent are smaller, by dry mass of soil

The filter should be noncohesive to be effective when cracks form. If it is not, the filter could sustain an open crack and fail to protect the cracked core. Similar design criteria can be used if a geotextile is used for the filter element.

Dams with dispersive cores on rock foundations should be given special consideration to prevent the clay from penetrating small rock cracks. This can be done by cleaning the cracks to a minimum depth of three times their width and by filling the cracks with cement mortar before slush grouting the core-rock contact. Dispersive clay modified with hydrated lime (Haliburton et al., 1975, Knodel, 1987) or a nondispersive clay of medium to high plasticity can also be utilized for this important embankment-foundation interface, depending upon the circumstance (Forbes et al., 1980; Logani, 1979; McDaniel and Decker, 1979; Sherard and Decker, 1977). Further details of foundation surface treatment are discussed in Bureau of Reclamation Design Standard No. 13, Chapter 3: Foundation Surface Treatment.

Great care should be taken when compacting soil adjacent to rigid structures such as conduits. In some cases, lime-modified dispersive clay has been used for portions of this interface. Lime modification of dispersive clay may be necessary for slope protection where other means such as gravel with the necessary filter layers are not economically feasible.

Where dispersive clay soils are present, there is always the danger of extensive erosion which can occur on both permanent slopes after construction or on temporary slopes during construction. In the case of permanent slopes, this erosion can lead to costly and difficult operation and maintenance. During construction severe erosion of a diversion gap or cutoff trench walls, for example, could lead to a changed condition and a possible contractor claim. All these conditions must be considered and analyzed during design of a structure and provisions made to minimize their detrimental effects.

Existing Dams or Embankments of Dispersive Clay

Many small homogeneous dams or embankments of dispersive clay throughout the world have functioned well for many years. It is highly unlikely that a dam or embankment that has retained a reservoir with no leaks, will develop a concentrated leak under ordinary conditions of reservoir operation. In the case of large dams retaining important reservoirs, especially if constructed with filters, it has generally been concluded there is no reason to consider them unsatisfactory under normal conditions, especially if no leaks were present for several years.

In situations where dams of dispersive clay have failed by piping and were repaired or rebuilt, lime-modified soil has often been used in repairing the breach and as slope protection (Perry, 1977; Sherard and Decker, 1977; Wegener et al., 1981).

SUMMARY

Dispersive clay soils are those with unique properties which under certain conditions deflocculate and are rapidly eroded and carried away by waterflow. These properties have and can result in disastrous consequences for earthfill dams or other hydraulic structures constructed with these materials. However, much is now known about the presence, properties, and tests for identification of dispersive clays and for their use in earthfill dams, earth embankments, other water conveyance or water-retaining structures, and various other civil engineering structures.

With the present state of knowledge of dispersive clays it is believed that no important changes are necessary in current practice for designing and constructing earth embankment dams or other important water resources structures (Sherard and Decker, 1977; Sherard et al., 1984b). However, it is important for the engineer to be able to identify dispersive clays on a given project so special care and attention can be given during design and construction to the critical areas in which they will be used. Recent filter research has shown that dispersive clays can be safely and effectively used if well designed filters are incorporated into the design. Several major dams have been built in the last few years using soils for impervious zones which were identified as dispersive clay. Lime-modified dispersive clays were used in certain critical areas in their construction (Forbes et al., 1980; Melvill and Mackellar, 1980).

In summary, safe dams and other hydraulic structures can be built with dispersive clay materials if certain precautions are taken. Precautions include, but are not limited to, proper moisture and density control, use of filters and filter drains, select placement of materials, use of sand-gravel blankets or lime-modified soil on slopes, and chemical treatment of dispersive clays. Without exception, dispersive clays identified to date, were transformed to a nondispersive state with the addition of 1 to 4 percent (by dry mass of soil) of lime $(CaOH)_2$. Any or all of the above methods may be used for specific parts of a structure, depending on materials available and on economics of each treatment.

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