

STABILITY OF EARTHEN-FILLED DAMS AS INFLUENCED
BY CHEMICAL AND MINERALOGICAL PROPERTIES
OF THE SOILS

By

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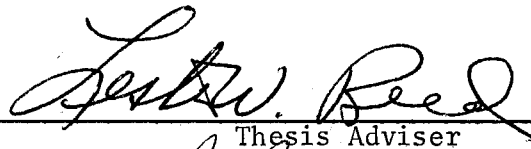
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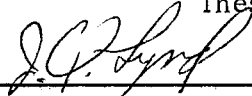
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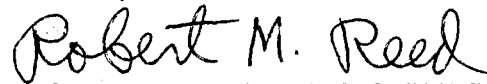
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CHAPTER I

INTRODUCTION

Small earth dams have been built for various purposes in many parts of the world. A few of these dams have failed not long after the dams were filled with water. From experience and study it has been found that most of these failures resulted from progressive erosion of a leak which developed through or under the dam. The failure probably was initiated by seepage through the micro-pore structure in loosely compacted embankments. This type of subsurface erosion is called "boiling or piping". Terzaghi (27) defined the characteristics of piping as subsurface erosion with discharge tunnels in the subsoil and by removal of particles through the action of the seeping water. According to many reports on several failed dams, there is no one specific fact which points out the main cause of the failure. There are many causes which have been proposed. From the engineering point of view the differential settlement and drying cracks are probably the most frequent cause of the leaks. Work in Australia and Israel (1,17) emphasized the importance of dispersive clay, E.S.P., S.A.R., and soluble salt concentration as factors which may help explain the cause of failure.

The main purpose of this study was to make an independent review of past experiences and to investigate some of the mineralogical properties of clays found in earthen-fill dams as a possible clue to erosion and failure.

CHAPTER II

LITERATURE REVIEW

During the last decade research studies on the failures of small dams have been carried out primarily in Australia. This work has provided new insights into the erodibility of clay soils used in the construction of dams (1,2,3,11,12,13,16,20,22,29). James and other (16) studied the cause of failure of a dam which was used to conserve water for a fire station and concluded that failure seemed to be due more to a combination of unfortunate circumstances and not one single factor. Dispersive clay is one of the important factors, and another factor that they believed to be involved was the dry state of the borrow material. The borrow material was moved during a drought and the dominant mineral in the soil clay was montmorillonite with illite subdominant and minor amounts of kaolin. Ingles, et al. (13) reported from their study of the Flagstaff Gully Dam that the factors which contributed to piping failure were deflocculation of sodium rich clay by a water of low salinity. They also considered the effect of E.S.P. and velocity of flow water. Their conclusion was in agreement with Wu (30) who proposed that in order for piping to occur in a dam or any earth embankment the velocity of seepage should exceed critical gradient; that is $i_{cr} = r - r_w/r_w$, where i_{cr} is the critical gradient, r is unit weight of soil, and r_w is unit weight of water. Aitchison and Wood (2) also suggested that in order to be safe the permeability should not exceed 1×10^{-5} cm/sec. Stephens (26)

correlated pedological soil classification with piping failure and he confirmed the correlation which exists between the incidences of failure and the character of soil profiles within the all of Great Soil Group soils of fine texture but failure was conspicuously absent in Kraznozems. Parker and Jenne (18) reported that piping occurs with the greatest frequency in the dryland soils of the world (arid and semiarid regions). In these regions, it occurs most commonly in valley alluvium which has been or is being trenched by gullies. Piping also occurs in the loess areas of the Mississippi Valley, where rainfall may exceed 50 inches per year. They also concluded from their study of the damage due to "piping" on western United States highways that regardless of location or material, there are at least four basic conditions which are essential for piping to develop. These four factors are: (a) sufficient water either to cause drainage through cracks or to saturate a layer of surface soil higher in permeability than the layers below it; (b) hydraulic head sufficient to move water through a subsurface route; (c) presence of permeable or deeply cracked soil or bedrock above a gully floor level; and (d) outlet for flow. Ingles and Aitchison (12) expressed soil erosion factors in another way which they called static factors and dynamic factors. A static factor is the existence of substantial porosity in the soil. A dynamic factor is the lessening of interparticle bond forces in the soil which is caused by water. They also pointed out that these interparticle bonds in natural soils may be: oxides of iron and aluminum, carbonates, bonding between clay particles, and concentrated or partially soluble salts such as gypsum. The clay-and-salt bonded soils when in the presence of water may seriously lessen the strength of the interparticle bonds which may result in dangerous consequences.

Aitchison, Ingles and Wood (1) studied the bond strength in soil and summarized their work as follows: those soil cations which provide the weakest bonding are the monovalent cations, and most prominent of these is the sodium ion. Therefore, saline and sodium enriched soils are particularly prone to this type of failure (1,2,11,29). According to Jackson (14) the dominant acidic cation under different pH soil conditions is the hydronium ion and the hydrated aluminum ion. In strongly acid soils the hydrated aluminum ion is predominate and these acid soils are not susceptible to ready dispersion. On the other hand, weakly acid soils of pH 5 or more, where the hydronium ion is predominate, soils should be, and are observed to be, susceptible to dispersion (12). The possible causes for this observation were, proposed by Sherard, et al. (24,25), as follows: that dispersive clay and hydraulic fracturing are the causes of piping in failed dams. There was no strong confirmation that the piping effect was due to montmorillonite clay according to Sherard, et al. (24,25). It has been reported that piping failures are more apt to occur in clay dams than dams built of silty sands and sandy silts which have little or no cohesion in the presence of water. Kassiff and Henkin (17) studied the physico-chemical properties of sound and failed dams in Israel and found that there was a correlation between total cation concentration, sodium absorption ratio (S.A.R.), exchangeable sodium percentage (E.S.P.) and the failed dam. From their study the soils of the failed dams had a cation exchange capacity (C.E.C.) above 150 m.eq. per 100 grams, S.A.R. above 25 and E.S.P. above 26. The correlation of S.A.R. and dispersive clays was confirmed by Aitchison and Wood (2) but their critical S.A.R. values were different from those of Kassiff. They also suggest the chemical additions and construction.

method to use if one is to prevent the possible failure of soil material susceptible to failure. Cole and Lewis (3) in their study of piping failures in small dams in Western Australian proposed that the soils most susceptible to failure were the highly plastic clays low in moisture content. Peterson and Iverson (19) investigated piping failure in three small dams in Canada. They concluded that the failure was due to dry construction material. They also found the dam embankment was very permeable and suggested that the mechanism of failure was similar to those reported by Volk (28) in that the slumping of the saturated lower portion of the embankment due to weight of the dry upper layer resulted in an arch through which water could flow to form a pipe. Emerson (7,8) suggested that piping was due to soil dispersion which in turn was due to high exchangeable sodium percentages in the soils. He suggested that the piping failure was caused by the flow of water along shrinkage cracks and he also described a simple dispersion test to detect dispersive soils and suggested that compaction pressure of 15 lbs. per square inch was sufficient to prevent piping failure. Fraser (10) attributed failure primarily to saturation settlement and this in turn was due to light compaction equipment and dry soil pipes in natural slopes in terms of soil dispersion and transportation. While several investigators were aware of the significance of E.S.P. as one factor or cause of failure, Fletcher, et al. (9) claimed that sodium may contribute to the severity of piping, but it is by no means necessary. They also reported five conditions that contributed to piping failure which were like those of Parker and Jenne (18). Rallings (20) investigated the cause of failed dams and believed that two conditions were necessary for an embankment to fail due to piping: (1) soil material that is susceptible to piping

failures must be a dispersive type; (2) the soils must be lightly compacted at low moisture contents. His results showed that dispersive clay was related to high E.S.P. and low soluble salt content. He also pointed out that pH, clay type, S.A.R. of the water are minor factors of soil dispersion. Several Australian investigators have concluded that there is a strong correlation between a rapid and simple dispersion test and the susceptibility of soil to piping. Emerson (5,6) studied the effect of clay minerals upon the slaking of soil crumbs, and he suggested that the salting depends on both the pressure developed by entrapped air in the pores and the degree of clay swell. He also suggested the classification of soil aggregates based on their coherence in water. Sherard (23) in his study of piping failure and erosion damage in soil clay dams in Oklahoma and Mississippi, used the rapid dispersion crumb test and divided the effect into four grades ranging from no reaction to strong reaction. The test consisted essentially of placing several soil crumbs in demineralized water, .001 normal sodium hydroxide and .006 normal sodium hydroxide and reading the amount of dispersion in each solution. Ralling (20) suggested that the use of distilled water be limited when the soils tested are high in E.S.P. and the pH is very low. He pointed out the advantage of using the 1 milliequivalent per liter of sodium hydroxide because the soil that is high in E.S.P. and low in pH will still disperse in 1 m.eq. liter sodium hydroxide and he believed dispersion to be associated with piping failure. Since the Exchangeable Sodium Percentage (E.S.P.) and Sodium Absorption Ratio (S.A.R.) were believed to be associated with the dispersive type of clay, Richards (21) related these two quantities by regression equations. Ralling (20) discussed the E.S.P. calculated from the cation exchange capacity and total

exchangeable cations which is the sum of Na^+ , K^+ , Mg^{++} , and Ca^{++} and determined which cation has the advantage in different soil conditions. In his study E.S.P. was calculated from C.E.C. however he pointed out that total exchangeable cations gave better correlation between E.S.P. and S.A.R. than the C.E.C.

CHAPTER III

MATERIALS AND METHODS

These experiments were performed in the soil chemistry laboratory of Oklahoma State University. Forty-nine soil samples were collected from several failed dams from various places and were investigated according to the procedures described below.

Rapid Dispersion Crumb Test

Five to ten grams of air dry soil crumbs, 1.50-2.00 cm. diameter, were dropped into a 250 milliliter beaker filled with deionized water. The beakers were allowed to stand for one hour or more; then the extent of the cloud of soil particles in the suspension around the crumbs was noted. If the water around the soil crumb was clear then the soil was considered to be non-dispersive. For the dispersive soils there was a cloud of soil colloids in the water around the crumbs and four categories of reaction were defined and employed to judge the test. The four categories followed were those of Sherard (23).

Reaction to Crumb Test

<u>Grade</u>	<u>Definition</u>
1	<u>No reaction</u> : Crumb may slake and run out on bottom of beaker;
2	<u>Slight reaction</u> : Bare hint of cloud in the water at the surface of the crumb. If the cloud is easily visible then the test

<u>Grade</u>	<u>Definition</u>
	indicates No. 3;
3	<u>Moderate reaction</u> : Easily recognizable cloud of colloids in suspension. Usually spreading out in thin streaks on the bottom of the beaker but does not cover the entire bottom area of the beaker;
4	<u>Strong reaction</u> : Cloud of suspended soil particles covers the bottom of the beaker, and usually in a very thin skin. In extreme cases all the water in the beaker becomes cloudy.

Identification by X-ray

The soil samples that showed dispersive properties were investigated by siphoning the cloud of dispersed soil particles into separate beakers. These colloids were then examined by means of X-ray diffraction in an attempt to identify the types of clay mineral. The method used to identify the type of clay was adapted from Jackson (15). The colloids in the sample were saturated with 1 normal calcium chloride and then the excess calcium ions were washed out. The samples were then washed with deionized water 3 to 4 times. The samples were placed on ceramic slides and examined by X-ray. After the initial run all slides were saturated with 10 percent ethylene glycol and then examined for expanded clays. Another portion of siphoned colloids was then saturated with 1 normal potassium chloride. The excess potassium ions were washed out, and the potassium saturated sample was placed on ceramic slides and examined by X-ray diffraction. The potassium saturated slide was then heated in a furnace at 550° C for 4 hours and again examined by X-ray diffraction. From the X-ray data collected the types of the clay were determined.

Then the soil crumbs were tested by the rapid dispersion test with 0.001 normal sodium hydroxide. Clouds of dispersed colloids were recorded according to criteria previously mentioned. These colloid suspensions were siphoned from the sample beaker and prepared for X-ray identification by the same treatment as described before. The grade of dispersion test and type of clay were compared between deionized water and 0.001 normal sodium hydroxide.

Sodium Absorption Ratio

As defined in many text books as

$$\text{S.A.R.} = \frac{\text{Na}^+ \text{ m.eq./}\ell}{\sqrt{\frac{\text{Ca}^{++} + \text{Mg}^{++}}{2} \text{ m.eq./}\ell}}$$

Soluble cations are expressed as milliequivalents per liter. Soluble cations are the ions that are present in equilibrium in the soil solution and not those adsorbed on the surface of the clay. As mentioned earlier in the literature review there is a correlation between S.A.R. and dispersibility of soil. The procedure in this study attempted to correlate the sodium to calcium plus magnesium ratio with the dispersibility of the soil. The soil samples were ground to pass a 20 mesh sieve and 10 grams of air dry soil samples were used. The procedure was essentially as follows: 20 ml. of ammonium acetate solution were added (pH 7.0) and shaken occasionally for 2 hours. The mixture was filtered through a Whatman No. 2 filter paper on a Buchner funnel into a 125 ml. flask. The sample was washed with successive 20 ml. portions of ammonium acetate four times or until filtrate total was 100 ml. If the filtrate

was not exactly 100 ml. the filtrate was made to the desired volume of 100 ml. Thus the solutions were ready for the determination of sodium, calcium and magnesium by means of atomic absorption spectrophotometer (Perkin-Elmer 303). From standard curve of each element the amount of sodium, calcium and magnesium ions were interpreted. Finally sodium absorption ratio was calculated from equation stated earlier. Although, this is not the standard method for S.A.R. it was believed that the total soluble and exchangeable cations removed by ammonium acetate exchange would give a reliable indication of the S.A.R. effect.

CHAPTER IV

RESULTS AND DISCUSSION

Soil samples used in this study were collected from 32 failed dam sites. The results of this study are reported in Tables I and II.

Grade of Dispersion: When the dispersion of soil crumbs in distilled water is compared to 0.001 normal sodium hydroxide it was noticed that soil crumbs tended to disperse more completely in 0.001 normal sodium hydroxide than in distilled water as shown in Figure 1. The data on the graph in Figure 1 shows the advantage of 0.001 normal NaOH over distilled water as a means of dispersing the soil crumbs from the soil samples studied. However, distilled water showed more advantage for dispersion where the E.S.P. was high and pH is very low, for example, a pH less than 4 or 5 (20).

Sodium Absorption Ratio: When S.A.R. was determined on the sum of the soluble ions and exchangeable ions the results were low in value when compared to S.A.R. values reported by Sherard (23), which were based only on the water soluble ions. The S.A.R., Na, Ca, Mg concentrations and the average grade of dispersion of soil crumbs in distilled water and in 0.001 normal sodium hydroxide are shown in Table II. The Sodium Absorption Ratio (S.A.R.) in this study showed no correlation with the degree of dispersion with the calculated "r" value which is +0.2543. While most of the references (2,17,20,23,25) showed a highly significant S.A.R. and the dispersion test of the soil crumbs, the results in this

TABLE I

CONCENTRATION OF EXTRACTED IONS, S.A.R., AND TYPE OF CLAY MINERALS IN THE
SOILS FROM FAILED EARTHEN FILLED DAMS

Sample	Mg	Ca	Na	S.A.R.	Type of Clay and Minerals
S-1	7.38	1.25	1.33	0.64	Kaolinite Quartz
S-4	10.17	1.65	1.16	0.48	Montmorillonite Quartz
S-6	6.00	1.10	0.77	0.41	Mica (illite) Kaolinite Quartz
S-9	4.25	1.70	0.66	0.38	Vermiculite Kaolinite Quartz
S-11	7.81	2.55	2.61	1.15	Vermiculite Mica (illite) Kaolinite Quartz
S-21	5.93	2.40	4.37	2.14	Mica (illite) Kaolinite Quartz
S-26	13.75	9.10	4.43	1.31	Montmorillonite Kaolinite Quartz
S-27	5.25	2.80	1.89	0.95	Kaolinite Quartz
S-29	7.83	1.78	7.05	3.22	Mica (illite) Kaolinite Quartz
S-32	21.00	6.90	0.14	0.04	Montmorillonite Chlorite Quartz
S-33	15.42	7.85	11.13	3.26	Montmorillonite Quartz
S-34	35.00	1.23	17.39	4.08	Montmorillonite Quartz
S-36	24.50	7.15	27.39	6.88	Mica (illite) Montmorillonite Quartz
S-40	16.25	1.78	5.05	1.68	Mica (illite) Kaolinite Quartz
S-58	11.08	2.80	0.11	0.40	Vermiculite Montmorillonite Quartz

TABLE I (Continued)

Sample	Mg	Ca	Na	S.A.R.	Type of Clay and Minerals
S-59	4.92	1.75	0.15	0.08	Mica (illite) Kaolinite Quartz
S-69	4.04	6.55	1.01	0.44	Mica (illite) Quartz
S-70	4.16	6.65	0.31	0.13	Mica (illite) Kaolinite Quartz
S-71	5.88	3.75	0.29	0.15	Mica (illite) Kaolinite Quartz
S-72	14.33	4.70	1.19	0.39	Mica (illite) Kaolinite Quartz
S-73	13.75	4.35	0.82	0.27	Mica (illite) Kaolinite Quartz
S-78.2	6.83	1.08	1.22	0.61	Montmorillonite Mica (illite) Kaolinite Quartz
S-79	5.08	0.95	0.59	0.34	Mica (illite) Vermiculite Quartz
S-86	3.79	0.78	0.59	0.39	Quartz
S-87	5.83	1.03	1.81	0.99	Montmorillonite Kaolinite Quartz
S-88	5.96	1.08	0.79	0.42	Mica (illite) Montmorillonite Kaolinite Quartz
S-89	6.75	1.00	0.72	0.37	Mica (illite) Montmorillonite Kaolinite Quartz
S-90	6.25	1.00	0.38	0.20	Quartz
S-91	5.82	1.03	0.32	0.17	Mica (illite) Vermiculite Mica (illite) Quartz
S-92	7.42	1.25	1.39	0.67	Montmorillonite Quartz Mica (illite)

TABLE I (Continued)

Sample	Mg	Ca	Na	S.A.R.	Type of Clay and Minerals
S-93	11.83	2.60	1.15	0.43	Montmorillonite Mica (illite) Quartz
S-94	14.25	3.65	1.52	0.51	Montmorillonite Quartz

TABLE II

Correlation Between Na vs. Mg Ions and S.A.R. vs. Grade of Dispersion^{1,2}

Sample	Na, X_1	Mg, X_2	S.A.R., X_3	Grade of Dispersion, X_4
S-1	1.33	7.38	0.64	3
S-4	1.16	10.17	0.48	2
S-6	0.77	6.00	0.41	3
S-9	0.66	4.25	0.38	3
S-11	2.61	7.81	1.15	3
S-21	4.37	5.93	2.14	3
S-26	4.43	13.75	1.31	1
S-27	1.89	5.25	0.95	3
S-29	7.05	7.83	3.22	4
S-32	0.14	21.00	0.04	1
S-33	11.13	15.42	3.26	4
S-34	17.39	35.00	4.08	4
S-36	27.39	24.50	6.88	3
S-40	5.05	16.25	1.68	3
S-58	0.11	11.08	0.40	2
S-59	0.15	4.92	0.08	3
S-69	1.01	4.04	0.44	2
S-70	0.31	4.16	0.13	3
S-71	0.29	3.88	0.15	3
S-72	1.19	14.33	0.39	2
S-73	0.82	13.75	0.27	2
S-78.2	1.22	6.83	0.61	3
S-79	0.59	5.08	0.34	3
S-86	0.59	3.79	0.39	3
S-87	1.81	5.83	0.99	4
S-88	0.79	5.96	0.42	4
S-89	0.72	6.75	0.37	4
S-90	0.38	6.25	0.20	4
S-91	0.32	5.82	0.17	4
S-92	1.39	7.42	0.67	3
S-93	1.15	11.83	0.43	3
S-94	1.52	14.25	0.51	2

¹ $n = 32$, $\bar{X}_1 = 3.12$, $\bar{X}_2 = 9.89$, $\sum x_1^2 = 1,009.87$, $\sum x_2^2 = 1,486.47$,
 $\sum x_1 x_2 = 870.45$, $r = +0.71^*$.

² $\bar{X}_3 = 1.04$, $\bar{X}_4 = 2.94$, $\sum x_3^2 = 65.55$, $\sum x_4^2 = 21.82$, $\sum x_3 x_4 = 9.618$,
 $r = +0.2543$.

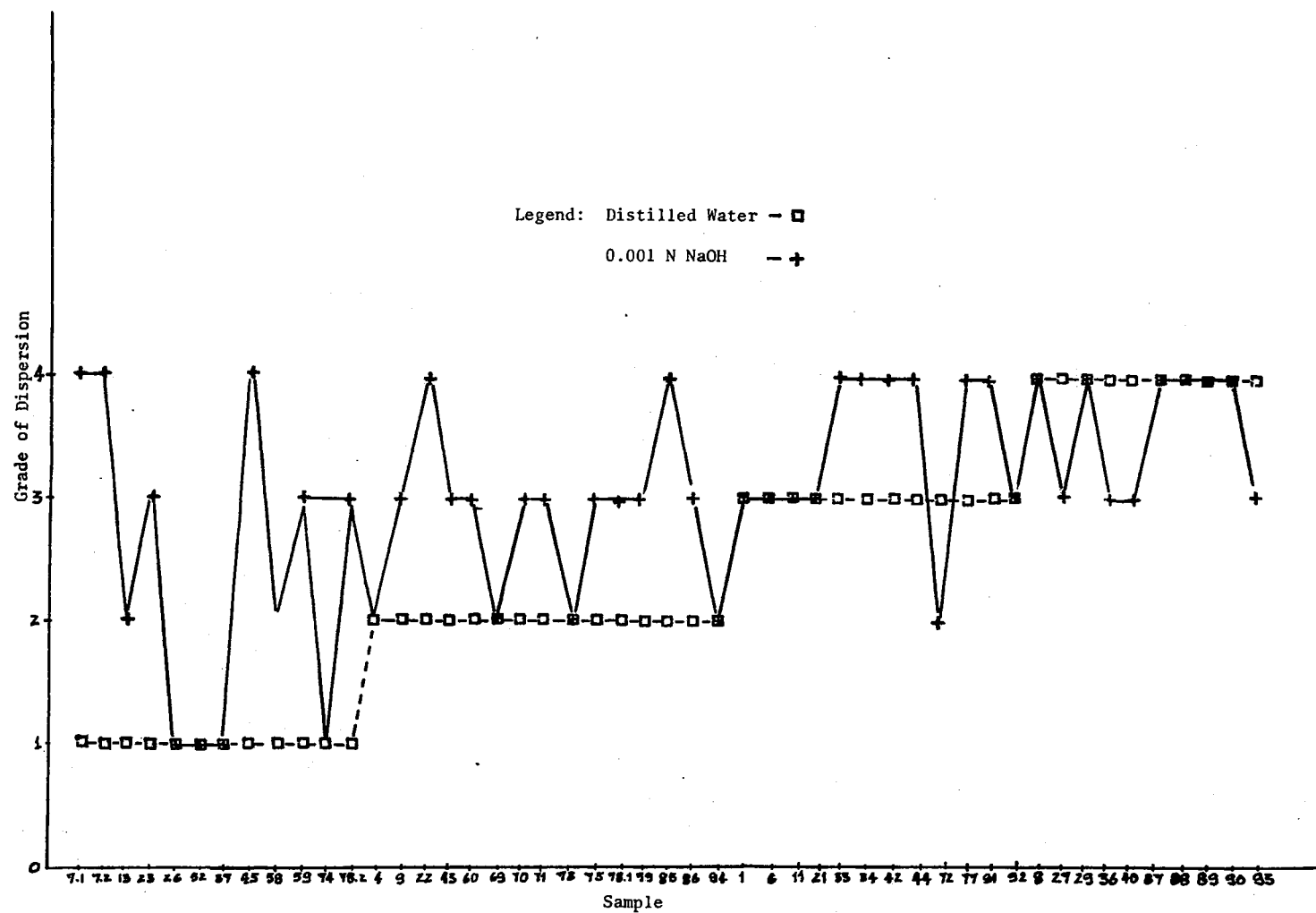


Figure 1. Grade of Dispersion of Soil Samples in Different Solvents

study showed no significant correlation between S.A.R. and dispersion, therefore, the dispersive properties of soil crumbs depend on the soluble Na, Mg and Ca ions and not on the exchangeable Na, Mg and Ca ions which are adsorbed on the surface of the clays. It is also very interesting to investigate the magnesium (Mg) to sodium (Na) ratio because in the writer's opinion a soil which is high in sodium, also tends to be high in magnesium. From statistical analysis there is a highly significant correlation between sodium and magnesium as shown in Table II. The results confirmed by this study pointed out that when the amount of sodium is high in the soils studied, the amount of magnesium will also be high.

Clay Mineralogy: The results of a study of the clay minerals are shown in Table I. As a general rule the soil is not composed of pure clays so that from Table I the results showed that the clay minerals which were detected by X-ray crystallography, are montmorillonite, vermiculite, chlorite, mica (illite), kaolinite and quartz. From these data it is not possible to report positively or to confirm montmorillonite as the major contributing factor or cause for the failure of these dams because X-ray diffraction is essentially a qualitative and not a quantitative procedure. Therefore the mineralogist is competent to identify the kinds of mineral present but he can not determine the amounts by X-ray procedures. However, there are other procedures beyond the scope of this study which are capable of measuring the quantity of a specific clay mineral present in a mixture (14). Although the results show that montmorillonite was present in almost all failed dam samples, there are some failed dam samples that did not show montmorillonite to be present by X-ray diffraction. The dispersion of soil crumbs by 0.001

normal NaOH gave better dispersion and more clay than distilled water as shown in Figure 1. Besides acting as a dispersing agent the sodium ion might have some effect on removing the inter-layer of montmorillonite. This type of effect may have caused the montmorillonite in sample S-11 to become visible on sodium saturation as shown in Figure 2. As a general rule soil samples are saturated with calcium or magnesium ions in an attempt to detect the type of clay mineral present by referral to standard diffraction patterns. Solvation with ethylene glycol allows separation of montmorillonite from vermiculite and chlorite by expanding diffraction spacing from 14 - 15 angstrom (\AA^0) to 17.7 - 18.0 \AA^0 . Saturation with potassium is to test the specimen for closure of vermiculite and montmorillonite interlayer while leaving the chlorite phase unaffected. Heating of a sample to 500 $^{\circ}$ C serves two important functions. It causes a collapse of vermiculite and montmorillonite which may contain nonexchangeable interlayer aluminum hydroxy complexes, and it destroys the kaolin minerals. When chlorite is present in a sample, it normally yields a second-order maximum at nearly the same position as the first-order maximum of kaolinite at 7.15 \AA^0 . If a 7.15 \AA^0 spacing, obtained from an unheated sample, and then disappears or decreases in intensity after heating at 500 $^{\circ}$ C, the presence of kaolinite is confirmed.

The X-ray diffraction data for sample S-11 does not show the presence of montmorillonite, vermiculite or chlorite in the colloid dispersed in distilled water, but these clay minerals are present when the colloid is dispersed in 0.001 normal NaOH as shown in Figure 2. Montmorillonite (smectite), vermiculite and chlorite were not detected on calcium saturation, potassium saturation or ethylene glycol solvation

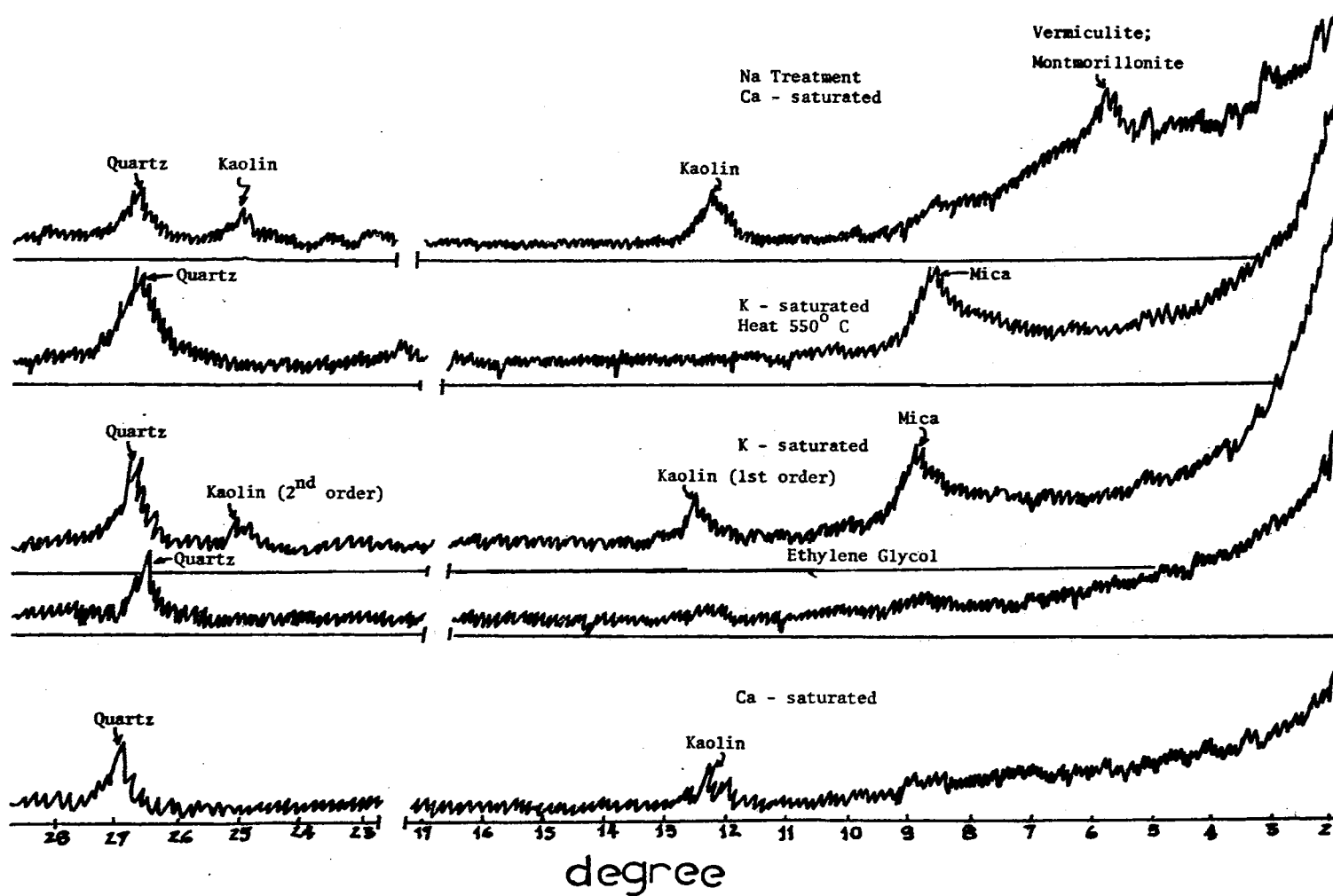


Figure 2. X-ray Pattern of Soil Sample S-11 in Different Treatments

of the calcium saturated sample. However, on heating the potassium saturated clays at 500°C a strong mica indication was observed at 9.90 \AA . This observation indicates that clay minerals particularly montmorillonite and vermiculite are probably strongly interlayered with hydrated iron and aluminum hydrated oxides. The presence of vermiculite and montmorillonite was confirmed when the soil colloid was dispersed by 0.001 normal sodium hydroxide as shown in Figure 3, sample S-78.2. In contrast to the data in Figure 3 the data shown in Figure 4, sample S-87, showed no diffraction maximum for montmorillonite, vermiculite, or chlorite with calcium saturation but with glycerol treatment the presence of montmorillonite was confirmed. Vermiculite or chlorite, however, were not present in this sample as shown by the absence of a 14 \AA diffraction maximum. The potassium saturated sample showed the presence of montmorillonite by the presence of a diffraction maximum at 12.4 \AA while mica (illite) or vermiculite collapsed to 10.0 \AA . The potassium saturated sample heated to 500°C confirmed the presence of mica, vermiculite, and montmorillonite and these results were the same for the soil colloid dispersed in 0.001 normal sodium hydroxide.

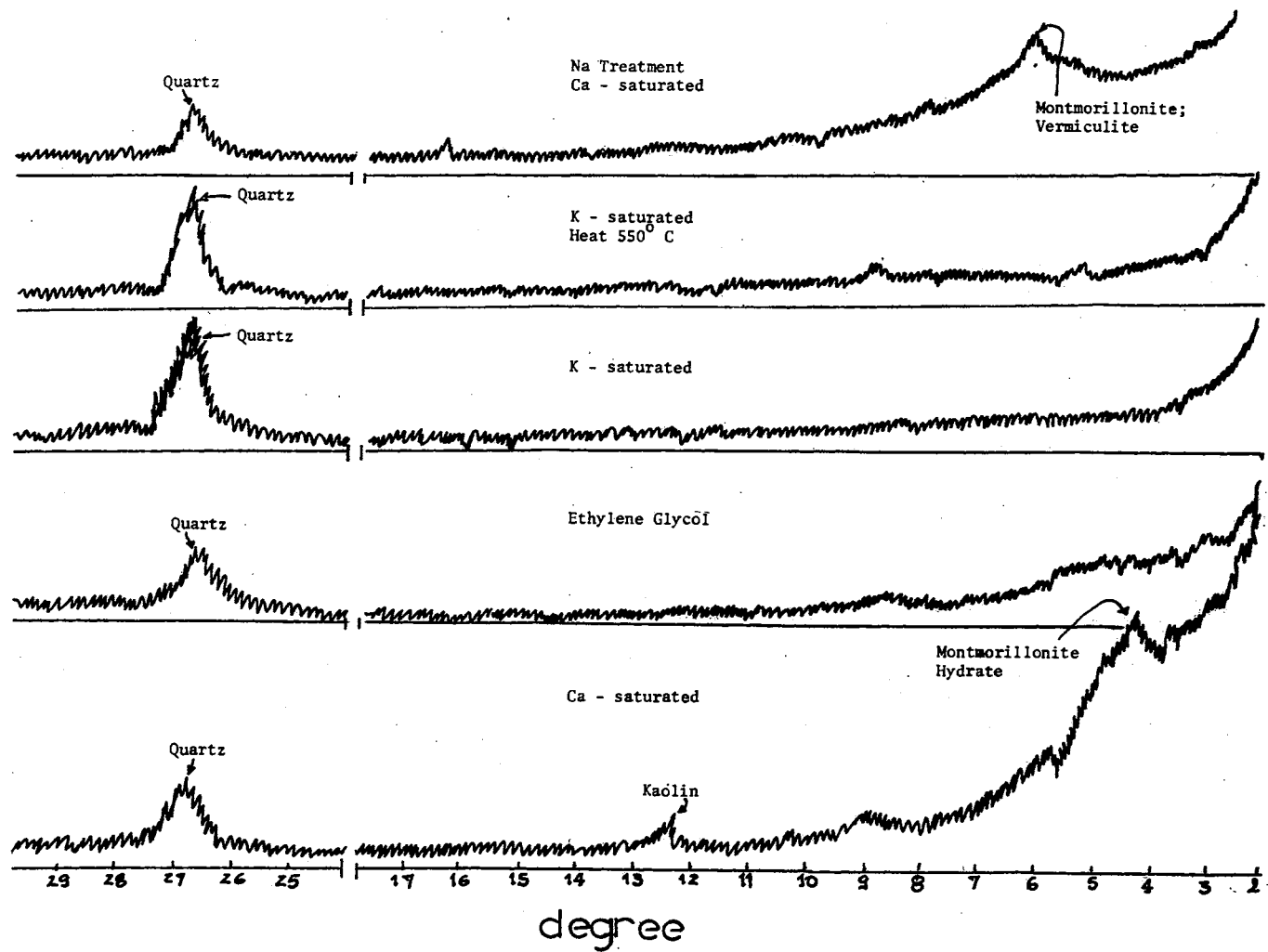


Figure 3. X-ray Pattern of Soil Sample S-78.2 in Different Treatments

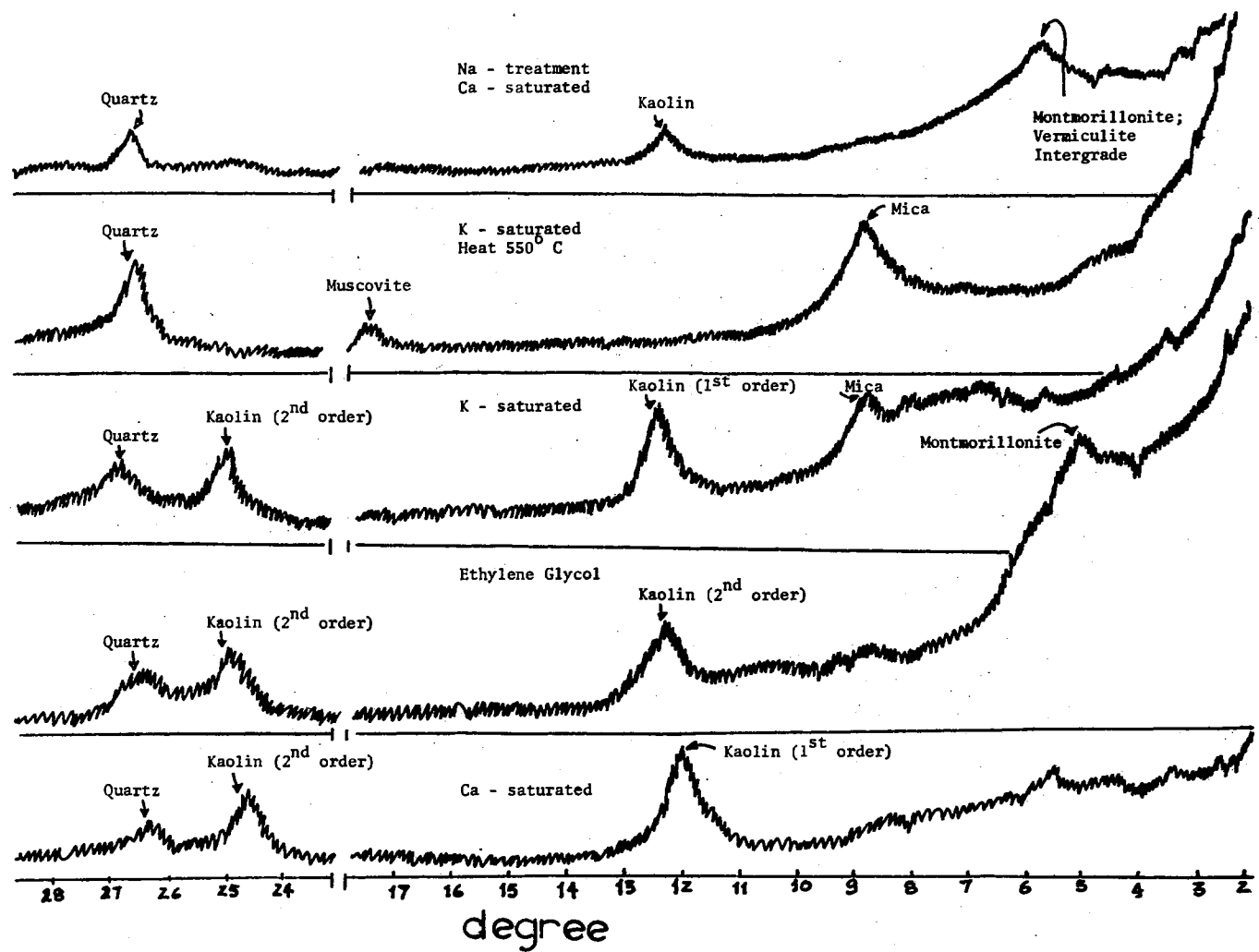


Figure 4. X-ray Pattern of Soil Sample S-87 in Different Treatments

CHAPTER V

SUMMARY AND CONCLUSION

The objectives of this study were: (1) to make an independent review of the past experiences and (2) to form opinions concerning the probable cause of the failure and erosion damage to earthen fill flood control dams. Soil crumbs from several failed dams were tested for their grade of dispersion, S.A.R. which was based on soluble and exchangeable ions and clay mineralogy.

Almost all soil crumbs from failed dams dispersed both in distilled water and 0.001 normal NaOH while the latter gave better results. However, there were some samples that did not respond to dispersion test.

Sodium Absorption Ratio as reported in this study gave a low value for almost every sample and showed no correlation with the dispersion of soil crumbs. Therefore S.A.R. which in this study was based on the amount of exchangeable and soluble ions is not a reliable way to measure the degree of dispersion of soil crumbs. All soil samples studied tended to be high in magnesium if the amount of sodium was high. This might be significant in future studies of the stability and failure of earthen filled dams.

Clay minerals in the soils studied were primarily montmorillonite, vermiculite, mica (illite), kaolinite and quartz.

From the results of this study it cannot be determined if there is only one single main cause of the failure of the dams. Failure seemed

to be more the result of a combination of unfortunate circumstances than of one single factor. These combination factors are: S.A.R. concentration of soluble salts, clay type which contributed to soil dispersion, the velocity of the seepage water, nature of sediment and method of construction.

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