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DISPERSIVE SOILS IN SOUTH AFRICA AND EARTH DAMS

SOLS DISPERSIFS DE L'AFRIQUE DU SUD ET BARRAGES DE TERRE

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SYNOPSIS: Dispersive soils undergo deflocculation in the presence of relatively pure water to form colloidal suspensions and as such are highly susceptible to erosion and piping. However, there is no threshold velocity for erosion of dispersive soil since the colloidal clay particles go into suspension even in standing water. Dispersive soils contain a higher content of dissolved sodium in their pore water than most ordinary soils. On the other hand there are no significant differences in the clay contents of dispersive and non-dispersive soils. Unfortunately they cannot be identified by conventional soil mechanics tests and so special dispersion tests are used.

Dispersive soils were first recognized in South Africa in the 1960's as a result of the failure of a number of small earth dams. They have a wide distribution. Soils in areas where Weinert's (1980) N-values exceed 2 may be particularly dispersive.

The use of dispersive soils for the construction of earth dams has led to serious damage and collapse due to piping. Dams using such soils, because there are no alternatives, must be built with careful compaction control during construction. The above is illustrated by discussion of dispersive soil characteristics and a case history of a dam failure due to poor construction.

INTRODUCTION

Dispersion occurs in soils when the repulsive forces between clay particles exceed the attractive forces. Hence such soils deflocculate in the presence of relatively pure water to form colloidal suspensions and therefore are highly susceptible to erosion. Damage due to internal erosion of dispersive soil leads to the formation of pipes and internal cavities on slopes. Piping is initiated by dispersion of clay particles along desiccation cracks, fissure and rootholes. Dispersive soils contain a higher content of dissolved sodium (up to 12%) in their pore water than ordinary soils. Their pH value usually ranges between 6 and 8, although the pH of the pore water sometimes can be on the acid side.

There are no significant differences in the clay contents of dispersive and non-dispersive soils, except that soils with less than 10% clay particles may not have enough colloids to support dispersive piping. In non-dispersive soil there is a definite threshold velocity below which flowing water causes no erosion. The individual particles cling to each other and are only removed by water flowing with a certain erosive energy. By contrast, there is no threshold velocity for dispersive soil, the colloidal clay particles go into suspension even in quiet water. Hence retrogressive erosion can occur at very low pore water flow velocities

The presence of exchangeable sodium is the main chemical factor contributing towards dispersive soil behaviour. This is expressed in terms of the exchangeable sodium percentage (ESP). A threshold value of ESP of 10 has been recommended, above which soils that have their free salts leached by seepage of relatively pure water are prone to dispersion (Elges, 1985). Soils with ESP values above 15%, according to Gerbe and Harmse (1987), are highly dispersive. Those with low cation exchange values (15 meq/100 g of clay) have been found to be completely non-dispersive at ESP values of 6% or below.

Another important property which governs the susceptibility of clayey soils to dispersion is the total content of dissolved salts in the water (TDS). In other words the lower the content of dissolved salts in the water the greater the susceptibility of sodium saturated clays to dispersion. Furthermore there is a threshold value for total dissolved salts in the pore water (for a given ESP) above which the soil remains flocculated. Nonetheless a soil with a high ESP and initially in a flocculated state (due to high salt content of the pore water) can be rendered dispersive by leaching of salts from the pore water.

The sodium adsorption ratio (SAR) has often been used to quantify the role of sodium where free salts are present in the pore water. The method is not applicable if there are no free salts present. Use of the SAR is based on the assumption that soils are in equilibrium with their environment. More specifically there is a relationship between the electrolyte concentration of the pore water and the exchangeable ions in the adsorbed layer of the clay particles. This relationship is dependent upon pH value and may also be influenced by the type of clay minerals present. Hence it is not necessarily constant. An SAR of more than 6 suggests that the soil is sensitive to leaching. According to Brink (1985) if the SAR is greater than 10 the soil is dispersive. However, in Australia soils in which the SAR exceeds 2 are regarded as dispersive (Aitchison and Wood, 1965).

A NOTE ON TESTING OF DISPERSIVE SOILS

Unfortunately dispersive soils cannot be differentiated from non-dispersive soils by routine soil mechanics testing. A number of physical tests have been used to identify dispersive soils, however, no single test can be relied on completely to identify them. One of the simplest tests is the crumb test. Although the crumb test generally gives a good indication of the potential erodibility of soils, a dispersive soil sometimes may give a non-dispersive reaction. The dispersion or double hydrometer test frequently has been used to assess the dispersiveness of soils. The test compares the content of 5 micron size which goes into suspension in a normal hydrometer test with the 5 micron size measured in a test in which the soil is dispersed. The modified hydrometer or turbidity ratio test is similar but compares a chemically dispersed soil in suspension with a naturally dispersed specimen. The pinhole test is another which has often been used to determine whether or not a soil is dispersive. Basically with this test dispersive soils fail under a flow caused by 50 mm head of water, intermediate soils erode slowly under 50 to 180 mm head of water, and non-dispersive soils give colloidal erosion under 380 mm head of water. Gerber and Harmse (1987), however, maintained that these physical tests are unable to identify dispersive soils when free salts are present, which is frequently the case with sodium saturated soils.

A number of chemical tests have also been used to identify dispersive soils. The saturation extraction test determines the amount of calcium, magnesium, sodium and potassium in the pore water. The total dissolved salts (TDS) is regarded as the sum of these four cations and is plotted against the sodium content expressed as a percentage of TDS to find whether the soil is non-dispersive, intermediate dispersive or dispersive (Sherard et al, 1976). The relationships are only valid for relatively pure eroding waters (such as TDS less than 0.5 meq/1 or about 300 ppm).

Gerber and Harmse (1987) argued that the determination of cation exchange capacity (CEC) by the summation of extractable cations is not valid if soluble salts occur in soil solution or if the base saturation of the soil is less than 100%. They recommend another procedure for identifying dispersive soils which is outlined in Figure 1. In this case, if the pH value as determined for a mixture of 20 parts of soil and 50 parts of distilled water, is higher than 7.8 and the ESP exceeds 5%, the soil is probably dispersive; if the ESP is above 15% the soil is dispersive; and if the ESP falls between 5% and 15% and the combined exchangeable sodium and magnesium percentage is greater than 15%, then the soil is generally dispersive. Unfortunately the influence on dispersion of different clay minerals and adsorbed magnesium is not clearly understood. There are cases on record in South Africa where ESP and EMgP values have exceeded 15% but no dispersion of consequence has arisen. Soils with a pH value lower than 7.8 can become dispersive on leaching if they contain free salts. In order to establish whether free salts are present a saturated soil paste is prepared with distilled water, and the electrical conductivity (EC) measured. If a value of more than 25 mS/cm is obtained at 15°C, then the saturation extract is analysed. These various tests show that the boundary between deflocculated and flocculated states varies considerably among different soils so that the transition between dispersive and non-dispersive type is wide. Because there is no clearly defined boundary between dispersive and non-dispersive soils it is usual to do several of the tests mentioned above on at least a proportion of all samples.

Although the Atterberg limits do not provide a means of identifying potentially dispersive soils, nonetheless the higher the values of plastic limit, liquid limit and plasticity index, the higher is the resistance to dispersion. For example, soils with high cation exchange capacity values and a plasticity index greater than 35% may swell so that potential flow paths may be sealed before erosion can proceed too far. Similarly the activity of a soil does not necessarily provide a parameter for distinguishing between dispersive and non-dispersive soils (Resendiz, 1977).

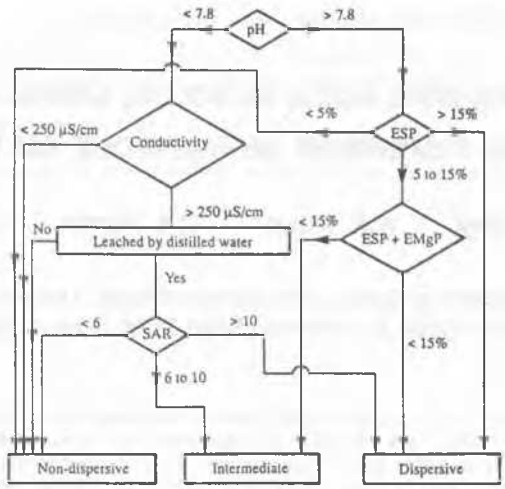

Fig.1 Procedure for identification of dispersive soils (After Gerber and Harmse, 1987).

DISPERSIVE SOILS AND EARTH DAM CONSTRUCTION

Serious piping damage and exceptional failures in earth dams have occurred when dispersive soils have been used in their construction. Experience, however, indicates that if an earth dam is built with careful construction control and incorporates filters, then it should be safe enough even if it has a core of dispersive clay. If no supply of clean pervious sand of the type used for a chimney drain is available, then a zone of silty sand or sandy silt can be considered as a line of defense against piping in dispersive soil used for a homogeneous earth dam. Such a chimney may not be pervious enough to act as a drain but it would be expected to prevent piping. Even so Sherard et al (1977) maintained that many homogeneous dams without filters, in which the dispersive clay has been properly compacted have experienced no leaks and so no failure has occurred. If a leak developed under unusual conditions such as cracking due to drying due to a long period of low water level or earthquake shock, then failure would occur. In order to increase the security of such a dam, a blanket of sand filter can be placed on the downstream side covered with a weighted beam.

A major problem of testing soils for safety against dispersion failure in earth dams has been the difficulty of defining a precise boundary between dispersive and non-dispersive soils. One of the main reasons for this is due to the fact that field performance depends on the quality of construction as well as the soil properties. Hence it is necessary to recognize soils which will not tolerate relaxed construction, in other words when satisfactory compaction must be attained. Maximum resistance to failure seems to occur at slightly wet of optimum moisture content. Accordingly lifts should be placed at 1.5 to 2% above optimum moisture content. Compaction should be continuous with no layer left exposed for any length of time otherwise it will dry out, so shrinking and forming fine cracks, which weaken the fill. Tadanier and Ingles (1985) proposed that soils used in earth dams should have an air voids percentage of less than 6 if unnecessarily dangerous conditions are to be avoided. They further suggested that a permeability of 10^{-7} m/s represents a threshold below which piping in dispersive soil does not occur. In addition they recommended the clay content of soil used in earth dams should exceed 20% and the linear shrinkage should be less than 7%.

Alternatively hydrated lime, gypsum and aluminium sulphate have been used to treat dispersive clays used in earth dams. The type of stabilization undertaken depends on the properties of the soil, especially the ESP and SAR. The quantity of hydrated lime applied to dispersive soil is determined from a series of laboratory tests made at differing percentages of lime additive. Normally plastic limit, liquid limit, shrinkage limit, dispersion and compaction tests are sufficient. It is suggested that the percentage of lime used should be that which raises the shrinkage limit to a value near saturation moisture content based on the compacted density to be achieved in the embankment. Usually lime treatment is applied to the outer 0.3 m of the surface of the embankment.

Due to its relatively low cost and solubility in water, gypsum can be used to treat dispersive soils. Because dispersive soils have a low permeability the gypsum must be mixed with the soil during construction. The quantity of gypsum added is equivalent to the excess sodium which it is required to replace in order to bring ESP values within the desired limits.

Aluminium sulphate or alum has also been added to dispersive clays. Although alum is highly soluble in water it only effects a cation exchange (i.e. it is not cementitious) and it is strongly acidic. About 0.6% aluminium sulphate, by dry weight of soil, is used to stabilize dispersive soil.

DISPERSIVE SOILS IN SOUTH AFRICA

Dispersive soils were first identified in South Africa in the mid-1960's as a result of the failure of a number of small earth dams in the Orange Free State and northern Cape Province (Donaldson, 1975). In South Africa dispersive soils have been derived from the Molteno Formation, the Beaufort Group, the Ecca Group and the Dwyka Formation, which are all part of the Karoo Sequence; the Witteberg Group, the Bokkeveld Group and the Table Mountain Group which belong to the Cape Supergroup; and the Malmesburg Group, the Cretaceous Enon, Kirkwood Formation and Sunday River Formation which are assigned to the Uitenhage Group. Put another way dispersive soils occur in regions which experience Weinert's climatic N values ranging between 2 and 10. Rainfall in such regions is less than 850 mm per year and typically occurs in summer as thunder storms. The exception occurs in south west Cape Province where the rainfall takes place during the winter months. Here the soils are largely derived from granites or Malmesbury mudrocks and can possess dispersive characteristics even where the ESP values are less than 5. A possible reason for this may be a high Mg content in relation to the Ca content. Where sediments contain large amounts of illite, montmorillonite or vermiculite with high ESP values, then dispersive soils usually are present. This is especially the case with soils in low lying areas developed from siltstones and mudstones of the Molteno Formation and Beaufort Group where the N-values are greater than 2. Under normal circumstances kaolinitic soils which have developed by weathering of granite are not dispersive. Nevertheless, some soils derived from granites are especially prone to the development of high ESP values in low-lying areas, particularly under anaerobic conditions where iron is mobilized as Fe^{2+}. The weatherable primary minerals from such rocks, orthoclase, albite, and muscovite, contain low concentrations of Ca^{2+} and Mg^{2+} ions and so high SAR values can develop. An important contributory factor is the fact that the K^+ ions are usually firmly attached in the interlayers of the hydromicas. In drier areas where N-values exceed 10, free salts tend to inhibit the development of dispersive soils even though high SAR values occur within the pore water, however, exceptionally dispersive soils can develop if the free salts are leached out.

In South Africa the occurrence of features like gullies and piping have helped identify dispersive soils. The subsoil frequently is highly shattered and exhibits a columnar or prismatic structure characteristic of a solonezy-type soil. Furthermore the occurrence of outwash fans which have a light colour may be indicative of the presence dispersive soils. Sometimes the occurrence of dispersive soils may be indicated by stunted growth of vegetation due to the highly saline condition of the soil. The presence of calcrete above a clay horizon could give rise to the formation of dispersive soils in that the bicarbonate ion, together with the effects of drying, could concentrate cations in the pore water after the calcrete has been precipitated. This leads to a change in the SAR of the pore water so that the ESP of the soil also increases. Nonetheless dispersivity can vary appreciably over small distances and particularly with depth.

A CASE HISTORY

A small earth dam, some 12 m in height, was constructed at Ramsgate, Natal, to impound a reservoir, the water from which was to be used for irrigation purposes. Two contractors were involved in the construction of the dam, the first giving up more less half way through the construction operation. The dam was completed at the beginning of January, 1984.

On the 14th January, 1984, some 200 mm of rain fell in the area which led to the rapid filling of the reservoir basin. On the afternoon of the 14th January, prior to the level of the water in the reservoir reaching the level of the spillway, a number of major transverse cracks developed across the crest of the dam wall. By the following morning the crest of the dam had sagged over that part of its length where the cracks had developed, and water was emerging from the dam at a number of points just above its downstream toe. This water flow became progressively worse, increasing in volume during the day, until by mid-afternoon headward erosion of some of the seepages merged causing a breach in the dam wall through which the reservoir water emptied (Fig. 2).

The investigation which followed the failure of the dam included check density measurements, using the sand replacement method, at representative locations on the

Fig.2 Failure of earth dam.

earth embankment (Fig. 3), as well as laboratory tests to determine particle size distribution (Fig. 4), Atterberg limits (Fig. 5), linear shrinkage and moisture content. The linear shrinkage ranged from 1 to 6%, with a mean value of 3.4%. The average value of the natural moisture content was 17%, varying between 15 and 19%. The pH value of the pore water, its content of sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg), its total dissolved salts, as well as the cation exchange capacity (CEC), exchangeable sodium percentage and sodium adsorption ratio of the soil material used for construction were also determined (Table 1).

Table 1 Chemical data for earth embankment.

	1	2	3	4	5	6	7
Extractable cations (meq/100g)							
Na	0.54	0.46	1.13	1.46	0.42	0.99	1.07
K	0.09	0.12	0.14	0.14	0.07	0.09	0.09
Ca	2.20	1.58	2.40	1.56	1.68	1.80	2.80
Mg	4.67	3.17	6.17	6.33	2.17	5.50	5.75
TDS	7.50	5.33	9.84	9.48	4.34	8.38	9.71
CEC	8.05	5.90	9.90	9.50	4.85	8.60	9.75
CEC 100g clay	38	30	44	43	23	40	46
ESP	7	8	11	15	9	12	11
SAR	0.9	0.9	1.7	2.3	1.0	1.6	1.7
pH	5.2	5.1	5.4	5.4	5.5	5.6	6.4
EC(mS/m)	77.5	64.8	105.6	98.6	98.6	70.4	119.7

Investigation of a drain installed beneath the dam to deal with seepage arising from a "spring" encountered when clearing the ground for construction, revealed the system to be intact and not to have any voids or loose material around it. The drain was located about a metre to the side and about a metre below the base level of the channel formed through the dam by breaching. Hence the presence of the drain did not contribute towards the initial settlement and transverse cracking, with subsequent breaching and failure of the earth dam.

The results of the investigation indicated that the main reason for the failure of the earth dam was poor compaction of the material of which it was constructed. In other words

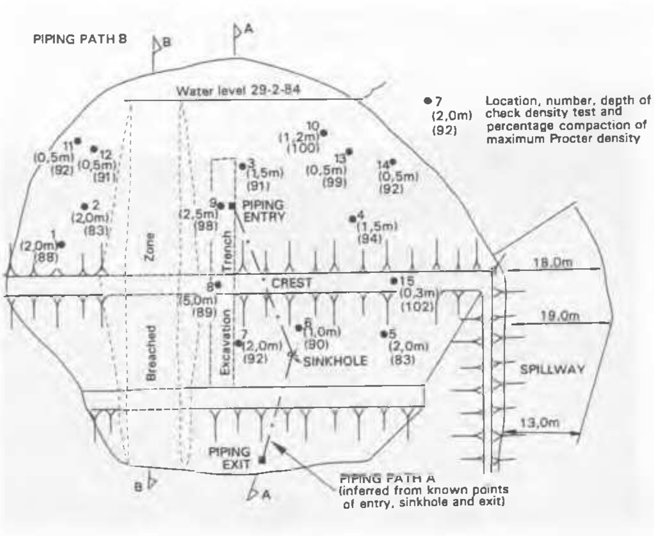

Fig.3 Location of check density measurements and samples.

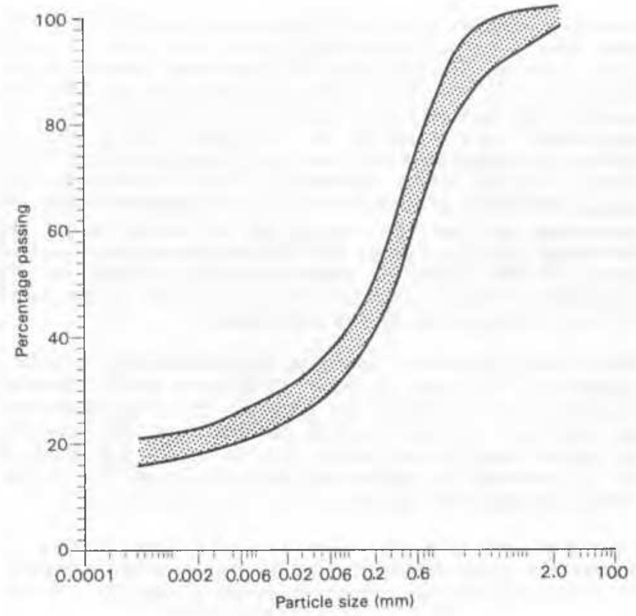

Fig.4 Particle size distribution of soil from the dam.

that only four of the check density tests passed the normal compaction requirement for the construction of earth dams (i.e. possessed a percentage compaction of 95% of Proctor maximum density or above). The average of the check density test results was 94% (including one result from the dam crest which may have been incorrect, neglecting this result would give an average of 92%) and two of the results were as low as 83%. These two results indicate that at the locations concerned the material did not undergo any appreciable compaction. Indeed it transpired that no compaction equipment was used to bring about proper compaction of the embankment during its construction carried out by the second contractor. The material was simply spread by a bulldozer and compacted by lorries placing the next layer.

Furthermore although a central clay core is normally incorporated in such earth dams and indeed had been recommended, a clay core was not incorporated into the dam by the second contractor. Accordingly the soil layers continued across the full width of the earth dam above the level achieved by the initial contractor.

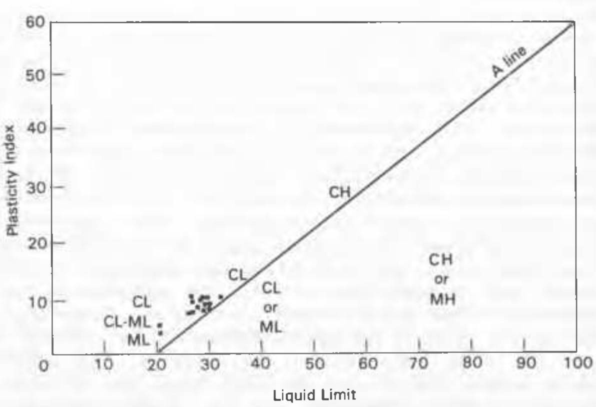

Fig.5 Plasticity chart of soil from the dam.

Yet another factor which contributed to the failure of the embankment was the dispersive nature of the clayey sand of which it was largely constructed. Material taken from the earth dam and subjected to chemical analysis had an exchangeable sodium percentage range extending from 7 to 15% (Table 1). As noted above, the presence of exchangeable sodium is the principal chemical factor contributing towards dispersive behaviour of soil. A threshold value of ESP of 10 can be adopted, above which soils which have their own free salts leached by seepage of relatively pure water are prone to dispersion. When the ESP of these soils was plotted against the cation exchange capacity per 100 g of clay, then they all fell within the dispersive soil zone, although some were near the marginally dispersive zone (Fig. 6). It is interesting to note that when the percentage sodium was plotted against total dissolved salts, all of these soils were non-dispersive. This would appear to support what Gerber and Harmse (1987) contended, that determination of CEC by summation of extractable cations is not valid if soluble salts occur in soil solution or if the base saturation of the soil is less than 100%. In no case did the plasticity index of these soils exceed 35%, indeed it never exceeded 10%, hence these soils were not self-healing.

The stages by which the earth dam failed and the immediate causes thereof were considered to be :-

1 Settlement of the embankment when it was saturated on first filling as evidenced by the settlement of the crest and the development of transverse cracks. This occurred as a result of the poor compaction so that the soil lost strength on saturation and became more compressible. Indeed the initial settlement, cracking and subsequent breaching of the dam occurred in the highest and weakest part of the embankment, and a stream channel occurred in this particular area before construction.

2 Movement of water along the soil layers within the embankment. This also was aided by poor compaction, whence the permeability was higher than it ought to have been.

3 Movement of water through the embankment, together with dispersivity of the soil which have rise to the development of five major piping tunnels through the dam. The piping tunnels on the upstream side of the dam developed approximately at the junction between the work of the second contractor and first contractors. On the downstream side of the dam they were located wholly within the part of the embankment constructed by the second contractor (Fig. 7). A "sinkhole" which developed on the downstream

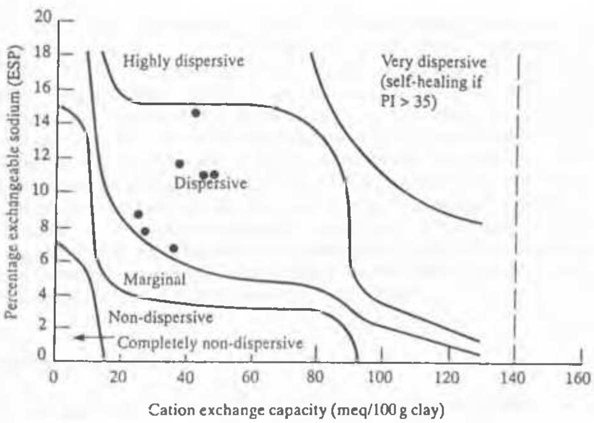

Fig.6 Gerber and Harmse (1987) determination of dispersion potential of soil from the dam.

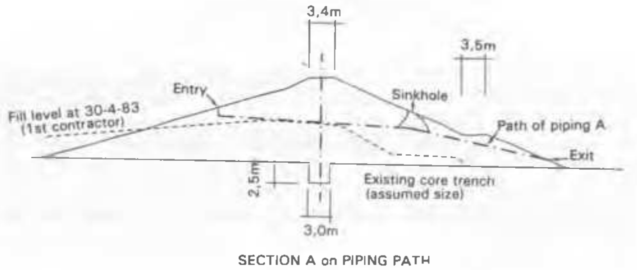

Fig.7 Section through earth dam showing zones constructed by first and second contractors path of piping and sinkhole location.

side of the dam (Fig. 8), together with excavations in the dam, helped locate the positions of the pipes. The piping tunnel inlets developed at around 4 m below the level of the crest of the dam, their outlets developing at the approximate level of the toe-berm on the downstream of the side.

4 Headward erosion and collapse of material into a pipe, as well as merging of a number of the pipes within the earth dam, caused the breach through which the reservoir water exited, which led to the failure of the dam.

Foundation settlement or movement of water through the foundation of the dam did not play any significant part in the failure of the dam. The ground on which the dam was built comprised very stiff to hard clay.

Because of the general poor compaction of the soil comprising the part of the earth dam remaining, it was recommended that there was no alternative but to completely reconstruct the dam after its demolition. The soil from the earth dam was stockpiled and used in the construction of the new dam which was properly compacted and possessed a clay core. It has performed satisfactorily up till now.

CONCLUSIONS

Dispersive soils are highly susceptible to erosion and piping, the dispersivity depending on the type of clay minerals present and the dissolved salts in the pore and eroding water. In South Africa such soils are generally

Fig.8 Collapsed sinkhole on downstream side of dam.

found in regions where the annual rainfall is less than 860 mm.

As dispersive soils can possess the same mechanical properties as non-dispersive clays, they cannot be identified by standard soil mechanics tests. Hence a number of special physical and chemical tests are used to recognize dispersive soils. Unfortunately no single test can be relied on entirely to identify these soils, so it is usual to carry out a number of tests on a selection of the soil samples.

Dispersive soils are widely distributed in South Africa and have given rise to problems when used in the construction of earth dams. For example, in the past this has led to serious damage and failure as a result of piping. The use of dispersive soils for the construction of earth dams is frequently necessary because there is no alternative material available. Dams using such soils must be built with careful construction control.

The failure of the earth dam in the case history quoted was primarily due to poor compaction of moderately dispersive soil which gave rise to piping failure. The situation was aggravated by the omission of a clay core in the upper part of the dam.

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