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The Effects of Capillary Action on the Consolidation and Shear Strength of Silt in a Hydraulic Fill Dam

Effets de la capillarité sur la consolidation et la résistance au cisaillement du limon dans un remblai hydraulique

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SUMMARY

In the gold-mining industry in South Africa the residue of crushed ore is disposed of in large hydraulic fill dams. The outer walls of these dams are built up of layers of material, each of which is allowed to dry before the next layer is placed. In order to study the stability of these walls, it was necessary to investigate the effects of drying on the consolidation characteristics and shear strength of the material of which they are built. Preconsolidation pressures on undisturbed samples and *in-situ* shear strengths were determined. These values were compared with those obtained from laboratory tests, where the effects of overconsolidation on the shear strength of the silt material were determined. It was found that, although heavy overconsolidation of the material occurred, the lasting increase in the shear strength was small because of the frequent rewetting.

SOMMAIRE

Dans les mines d'or de l'Afrique du Sud, on jette le résidu du minerai broyé dans des barrages à remblai hydraulique. Les murs extérieurs de ces retenues sont construits de couches de matières qu'on laisse sécher avant de déposer la couche suivante. Pour étudier la stabilité de ces murs, il fallait examiner les effets de dessèchement sur les caractéristiques de consolidation et sur la résistance au cisaillement des matières dont ils sont construits. On a mesuré les pressions de préconsolidation sur des échantillons intacts et les résistances au cisaillement *in situ*. On a comparé ces valeurs à celles obtenues des essais en laboratoire où on avait déterminé les effets de surconsolidation sur la résistance au cisaillement du limon. Bien que la matière fût fort surconsolidée, on a trouvé que l'augmentation durable de la résistance au cisaillement était limitée à cause des mouillages fréquents.

IN THE GOLD-MINING INDUSTRY, which is of major importance in South Africa, the quartzitic conglomerate ore is milled to a fine powder from which the gold is extracted by the cyanide process. The residue, known as slimes, is a silt consisting mainly of quartz and sericite mica particles, with small quantities of pyrites, other minerals, and salts. Typical particle size distribution curves are shown in Fig. 1. The residue is mixed with an equal volume of water and then pumped to slimes dams for disposal. An average mine produces about 100,000 tons of slimes solids per month. As the life of the mine may be 25 years, the volume of material disposed of is very large and some slimes dams cover an

area of one million square yards and rise to a height of over 100 feet.

The slimes suspension is delivered to the highest point on the site and is distributed around the periphery of the dam by gravity flow. At any point where building is required, the suspension is retained in paddocks, or areas bounded by hand-built walls about one foot high. The solids settle in two days and then the clear water is drained. The layer of slimes, which is about two inches thick, is then left to dry for a period of two weeks before the next layer is deposited. Whenever it becomes necessary, the paddock walls are raised by digging and packing some of the slimes material. In this way an outer wall 200 feet thick and with an outer slope between 25° and 45° is built. Slimes which is not required for building of the outer wall, the excess water draining from the wall, and stormwater are all contained in the central area of the dam from where the water is removed by "glory-hole" spillways.

It has been contended for many years that the stability of these dams is largely dependent on the increase in shear strength due to the effect of capillary forces in the outer walls. An investigation of the stability of these dams (Donaldson, 1960) was begun by making field measurements.

FIELD PROGRAMME

A section of the outer wall of the East Geduld slimes dam was selected for the field investigation. Three boreholes were put down in an area where the dam was 65 feet high. The phreatic surface was found between 30 and 50 feet. Below the phreatic surface the holes collapsed and it was extremely

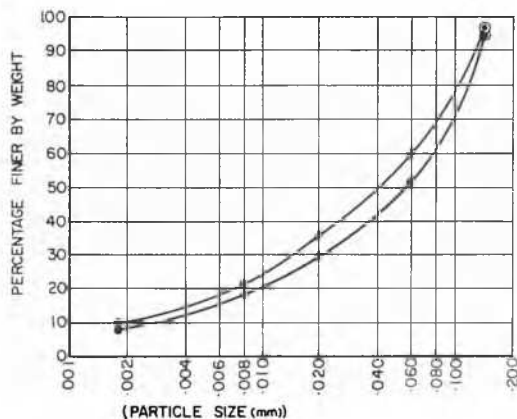


FIG. 1. Particle size distribution of slimes material from East Geduld slimes dam.

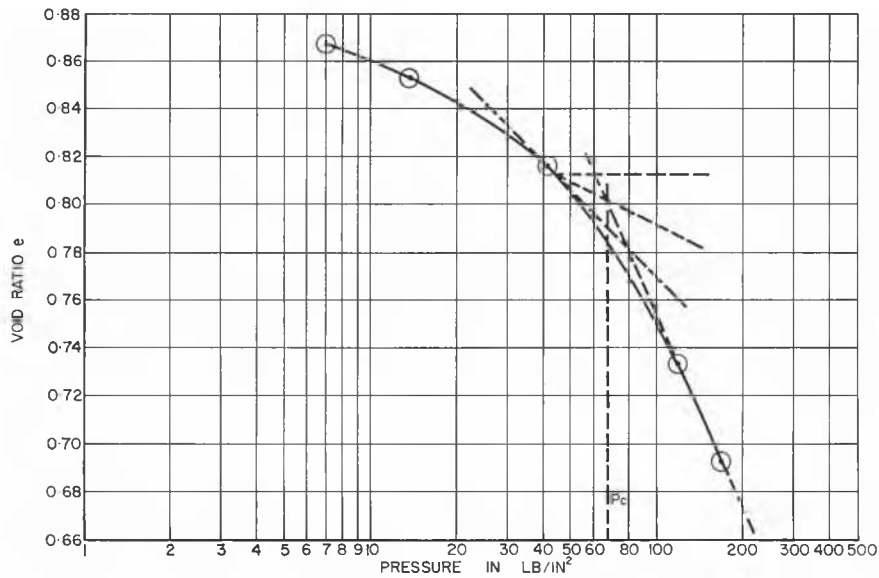


FIG. 2. Consolidation curve for undisturbed slimes sample from East Geduld slimes dam.

difficult to obtain samples. Undisturbed samples were taken at four-foot intervals by means of a three-inch-diameter thin-wall piston sampler and by using the "shoestring" method of sampling (Collins, 1954). *In-situ* vane shear tests were carried out alternately with the sampling.

Small undisturbed samples were cut from the three-inch-diameter samples for density, void ratio, and moisture content determinations. The results of these tests showed such a random scatter that no correlations could be found. These variations are attributed to minor changes in the particle size and nature of the slimes, the arrangement of the flaky particles, and the lack of knowledge as to whether the material was on a rebound or reconsolidation cycle at the time of sampling.

PRECONSOLIDATION PRESSURES

Normal oedometer tests were performed on the three-inch-diameter undisturbed samples. Although the void ratio *versus* log pressure plots have a gradual curve, as can be seen in Fig. 2, the preconsolidation pressure could be determined

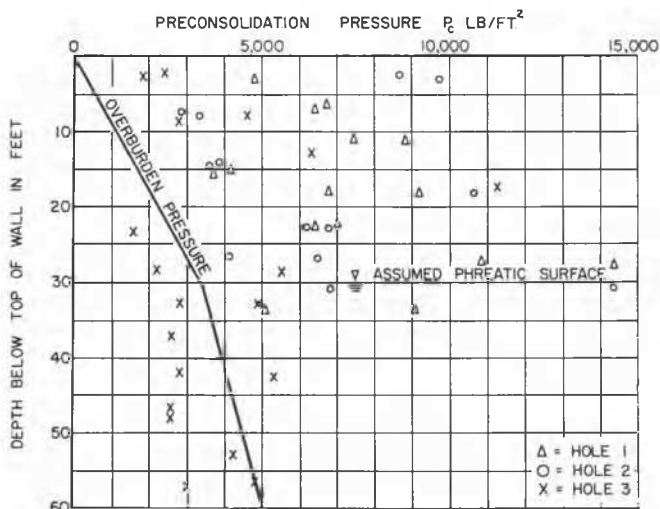


FIG. 3. Preconsolidation pressure *versus* depth plot for samples from East Geduld slimes dam.

reasonably accurately using Casagrande's construction (Taylor, 1948). Preconsolidation pressures are shown plotted against depth in Fig. 3.

Also shown in Fig. 3 is the overburden pressure which was calculated by using the average density of 111 lb/cu.ft. above the phreatic surface and the submerged density of 56 lb/cu.ft. below the phreatic surface. The phreatic surface was assumed to be 30 feet below the top of the wall. It will be seen that the great majority of results fall well above the overburden pressure line, especially above the phreatic surface. The difficulties of sampling the very moist material have already been mentioned and the values which fall below overburden pressure line must be attributed to sample disturbance.

The only explanation for the overconsolidation of the slimes is that capillary action takes place. The stress conditions in the non-saturated material above the phreatic surface at the time of sampling were not known. Therefore all that can be said is that the maximum intergranular pressure, which was reached at some stage during the numerous drying and wetting cycles, was the preconsolidation pressure.

LABORATORY DESICCATION TESTS

The effective or intergranular stress in the soil may be expressed (Bishop, *et al.*, 1960) as:

$$\sigma' = \sigma - u_a + \chi(u_a - u_w), \quad (1)$$

where σ' = effective or intergranular stress; σ = total normal stress; u_a = pressure in the air in the pores; u_w = pressure in the pore water; χ = factor relating equivalent pore pressure, \bar{u} , to the actual pressures in the air and water in the pores. In the quasi-saturated state (Aitchison, 1956) where all the pores are full of water, that is under capillary tension, χ is unity and Eq 1 becomes:

$$\sigma' = \sigma - u_w. \quad (2)$$

It was, therefore, decided to experiment within the quasi-saturated range by allowing a slimes slurry to dry out while the pore water pressure, u_w , was being measured by means of tensiometers. The tensiometers were similar to the two-lead piezometers used in earth dams (Penman, 1953).

It was found that between six and eight days after a layer was deposited, negative pore water pressure developed and built up very rapidly. On rewetting, the release of the suction was almost instantaneous and, with further drying, suction of the previous magnitude was attained within 24 hours. Measurements made at different depths in a four-foot-deep section of slimes showed very little time lag between suctions at the different depths. This was due to the shrinkage cracks which extended to the bottom of the layer.

Preconsolidation pressures were determined on samples cut from this material at the completion of the tests. There was, however, a time lag between the last available pore water pressure reading and the cutting of the samples. As a result, the preconsolidation pressures were in excess of the intergranular pressures calculated from Eq 2, using the maximum measured negative pore water pressure. It is interesting to note that in one case where a delay of more than a day occurred, the preconsolidation pressure was 6,900 lb/sq.ft. which is of the same order as the preconsolidation pressures measured in the field and shown in Fig. 3.

In-situ VANE SHEAR STRENGTH

Although the material was silt it was predicted that, because of its desiccation, it would behave as a cohesive material. It was therefore decided to use the *in-situ* vane shear test to determine the natural shear strength. The results of these tests are shown in Fig. 4, in which the shear strength for a normally consolidated material with an angle of shear resistance of 35° is also given.

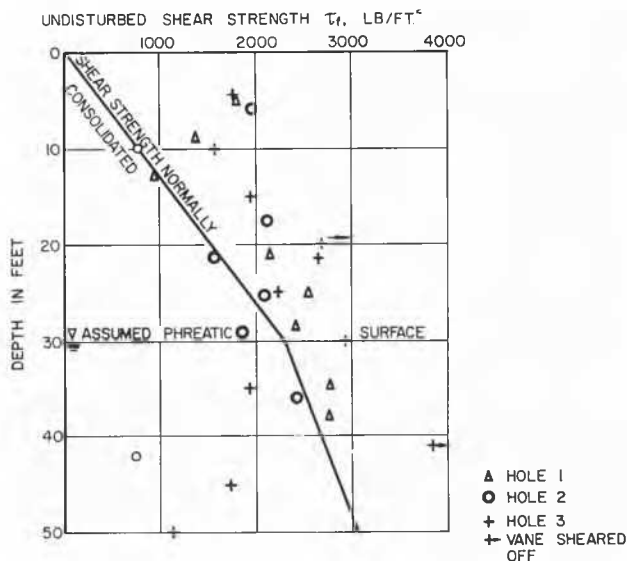


FIG. 4. *In-situ* vane shear strengths, East Geduld slimes dam.

Once again it will be seen that the majority of values show a higher shear strength than would be expected from a normally consolidated material. The relatively low values found below the phreatic surface must be ascribed to disturbance of the soil caused by jetting and driving the casing and to hydraulic uplift forces. The ratio between undisturbed and remoulded shear strength had an average value of eight and the remoulded strengths were all below the values for normally consolidated material. This low remoulded strength is not unexpected in a loosely packed granular material.

The increase in shear strength or apparent cohesion may be due to two causes: either the effect of the overconsolidation described previously or the contribution to shear strength

caused by the negative pore water pressure present at the time of testing. It was, therefore, necessary to carry out further investigations in the laboratory.

LABORATORY SHEAR INVESTIGATION

The measurement and control of negative pore water pressures during shear tests is very difficult. The direct measurement of the effects of overconsolidation on desiccated slimes samples was therefore not attempted. Instead it was assumed that the effects of overconsolidation would be the same regardless of whether overconsolidation was caused by desiccation or by applying a greatly increased load and then removing it once full consolidation had taken place.

This latter approach was used in the laboratory tests. A standard 1½-inch triaxial compression testing machine was used. The drainage and pore water pressure measuring systems of the triaxial cell were filled with air-free water, leaving a film of water above the porous base plate. The rubber membrane was then attached to the base plate and a split 1½-inch-diameter sample mould was placed round the membrane and over the base plate. The mould was held in position with two rubber rings and the top of the membrane was stretched over the top of the mould. Air-free water was then run into the bottom of the membrane from the burette of the drainage system, until it was about ⅜ inch deep. Filter paper was then placed on the base plate under the water to prevent air bubbles being trapped underneath it. Strips of filter paper for vertical drains were moistened and placed on the inside of the membrane.

Slimes and water were mixed to a thick slurry which was poured slowly into the sleeved mould. The mixture was stirred and agitated during pouring to prevent air bubbles being trapped. The mould was filled to the top but, when the solids had settled, the top of the sample was ⅜ inch below the top of the mould. The sample top cap and the filter paper were then carefully placed in the water on top of the sample and the top of the membrane was released to fit round the top cap. Once any air bubbles were smoothed out, the sealing rings were placed round the membrane and the top cap. The triaxial cell was then screwed on and a consolidating pressure of 5 lb/sq.in. was applied while the drainage system was left open. After two hours sufficient consolidation had occurred to allow the sample to stand unsupported. The drain cock was closed, the cell was emptied, the split mould was removed, and then the cell was replaced. The full consolidating pressure was then applied and the drain cock was opened.

Burette readings were taken to record the consolidation process. Although 90 per cent of consolidation occurred within the first hour, the samples were left under the consolidating pressure from 18 to 24 hours. If an overconsolidated sample was required, the drainage tap was left open and the cell pressure was reduced to the testing pressure. The sample was then left for a further 24 hours to permit full rebound to occur. Before beginning the test the drain cock was closed and during the test the pore water pressure was measured by means of a closed manometer system (Collins, 1957).

In the first set of tests the slimes were normally consolidated. The Mohr circles expressed in terms of effective stress for these tests are shown in Fig. 5 where the maximum value of $(\sigma'_1 - \sigma'_3)$ was considered to be the failure criterion. The effective cohesion intercept is zero and the angle of effective shearing resistance is $\phi' = 35^\circ$. A similar analysis using the maximum value of (σ'_1 / σ'_3) as the failure criterion also gave a line passing through the origin but with $\phi' = 36^\circ$.

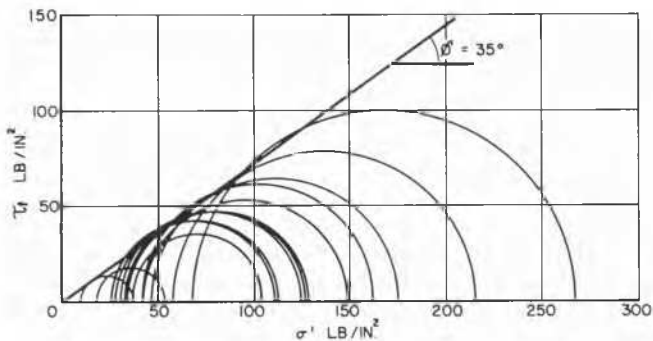


FIG. 5. Mohr circles expressed in terms of effective stress for compression tests on normally consolidated slimes samples.

shear strength of normally consolidated soils may then be expressed (Hvorslev, 1938) as:

$$\tau_f = \sigma'_{cr} \tan \phi_{cr}, \quad (3)$$

where ϕ_{cr} is the angle of shearing resistance with respect to σ'_{cr} and is not necessarily equal to ϕ' . In this case $\phi_{cr} = 36^\circ$.

The results for the rebounded tests are shown in Fig. 6. The overconsolidated material shows much greater shear strength than the normally consolidated material except at very low rebound pressures. It is possible to redraw Fig. 6 using a series of straight lines as shown in Fig. 7.

CONSIDERATION OF LABORATORY AND FIELD RESULTS

By assuming the rebound pressure to be the overburden pressure and using the preconsolidation pressures measured in the field and shown in Fig. 3, it was possible to derive equivalent shear strengths by interpolation of the laboratory results. The interpolated points are shown in Fig. 7. The predicted shear strengths and the *in-situ* shear strengths are plotted in Fig. 8.

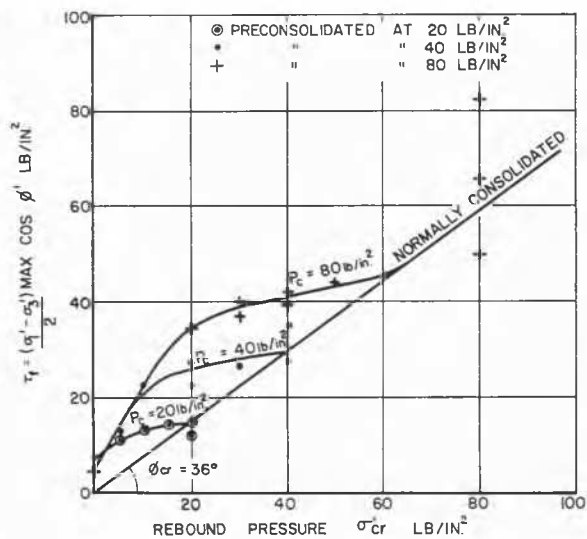


FIG. 6. Effect of overconsolidation on shear strength of slimes.

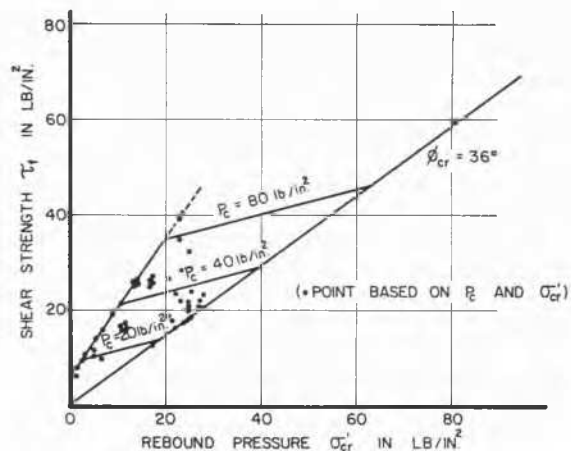


FIG. 7. Shear strength related to preconsolidation and rebound pressures.

The rebound tests were carried out on samples preconsolidated at 20, 40, and 80 lb/sq.in. In these tests it was decided to use the maximum value of $(\sigma'_1 - \sigma'_3)$ as the failure criterion. The results are expressed in terms of the preconsolidating pressure, P_c , and the rebound pressure, σ'_{cr} . The

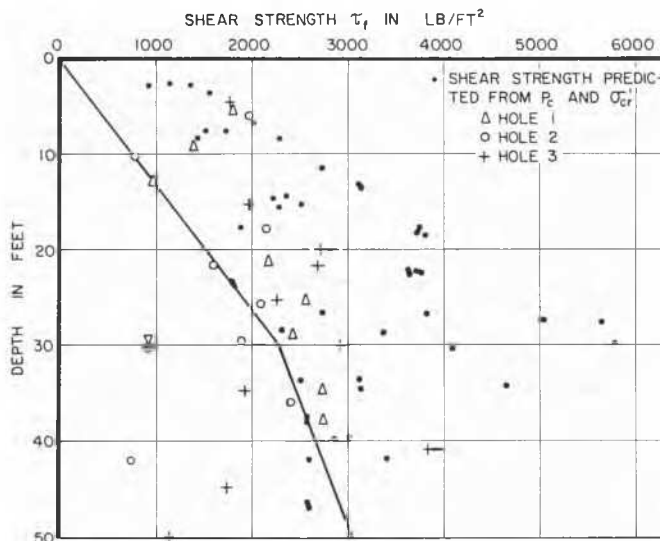


FIG. 8. Predicted and measured shear strengths at East Geduld slimes dam.

It will be seen that near the top of the wall the *in-situ* shear strength agrees very closely with the predicted shear strength but that lower down the predicted shear strength is considerably greater than the measured shear strength. The reasons for this can be found in the process of construction of these walls.

The slimes is laid down wet and then heavily overconsolidated by capillary action. When the next layer of slimes is deposited the capillary forces are released and the material is rebounded to the overburden pressure, which is virtually zero, and Fig. 6 shows that the shear strength will also be very small. This process will be repeated with every layer that is placed. As the thickness of slimes above a specific layer increases, the fluctuation of the magnitude of the capillary forces should decrease. At some stage during this cycling process the combination of preconsolidation pressure and rebound pressure, which will give the maximum retainable shear strength, will be reached. These need not necessarily be the highest pressures reached in each case.

The effect of the negative pore water pressure in the material at the time of the *in-situ* testing cannot be overlooked. It has not been possible to measure these pressures

but an equivalent negative pore pressure of 15 lb/sq.in. would have been sufficient to cover all the *in-situ* shear strengths. The preconsolidation pressures are evidence that far greater pressures than this can develop in slimes dams. On the other hand, the relatively high shear strengths measured below the phreatic surface, where there were no capillary forces, can only be attributed to the results of overconsolidation. The rate of vane testing and the permeability of the material preclude increases in strength due to dilatancy.

CONCLUSIONS

The laboratory tests have shown that overconsolidation of the fine-grained granular material does increase considerably the shear strength at high rebound pressures but that the shear strength decreases very rapidly at low rebound pressures. Consideration of the numerous wetting and drying cycles to which the material is subjected leads to the conclusion that, although high capillary consolidation pressures may be exerted at times, the lasting effect of this overconsolidation on the shear strength of the material may not be so great. The measured preconsolidation pressures and the *in-situ* shear strengths bear this out.

Equivalent negative pore pressure will also contribute to increased shear strength during dry periods. When the material is wet, however, the strength due both to overconsolidation and negative pore pressure will be reduced to a minimum. When slip failures do occur, they happen after periods of prolonged rainfall, as might be expected.

In considering the stability of these dams, the effects of

capillarity are not taken into account as a definite part of the shear strength but are accepted as an additional, if unknown, and variable factor of safety.

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