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G. W. Plant

Ove Arup and Partners

P. B.B. Voslo

Consultant Waste Water Purification, Geustyn, Forsyth and Joubert Inc.

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The Failure of a Soil Blanket Lining Caused by the Action of Bacteria

G. W. Plant
Partner, Ove Arup and Partners

P.B.B. Voslo
Specialist, Consultant Waste Water Purification, Geustyn, Forsyth and Joubert Inc.

SYNOPSIS A raw water storage reservoir was constructed with earth embankments and a soil blanket floor lining. Treated sewage effluent was used as construction water. Bacteria in the soil were capable of converting the organic nitrogen and ammonia present in the effluent to nitrite and then to nitrate under aerobic conditions. This nitrate was reduced to nitrogen gas under anaerobic conditions. The generation of gas had a "leavening" effect on the soil structure of the floor lining leading to a high water permeability, thus making the soil lining ineffective.

INTRODUCTION

This case history relates to a raw water storage reservoir built for an installation in the Eastern Transvaal, South Africa, between 1977 and 1979, and which experienced excessive seepage through the floors. The two compartment oval reservoir has overall plan dimensions of about 600m by 400m and has a total capacity of 885,000m^3. The 8m high division and perimeter embankments have external and internal slopes of 1 on 3, the latter having a 400mm thick rock rip-rap, underlain by a geotextile. (Fig. 1). There is a blanket drain within the homogeneous embankments from which are led a number of outlet pipes. A soil blanket lining 0.5m thick was constructed over the floors.

Site Investigation

Investigation at the reservoir site comprised small diameter cored boreholes, large diameter trial holes and test pits. Permeability tests were carried out in the boreholes within the rock formations at test pressures appropriate to the proposed reservoir top water level. The northern area of the site is underlain by Felsite lavas of the Rooiberg Group. The southern portion is underlain by Karoo sediments of the Ecca and Dwyka Groups comprising shales, siltstones and sandstones (Fig. 2). The entire area is covered by a thin layer of transported soil (metastable aeolian sand) and residual soils. Ferruginized gravel in a sandy matrix occurs over much of the site.

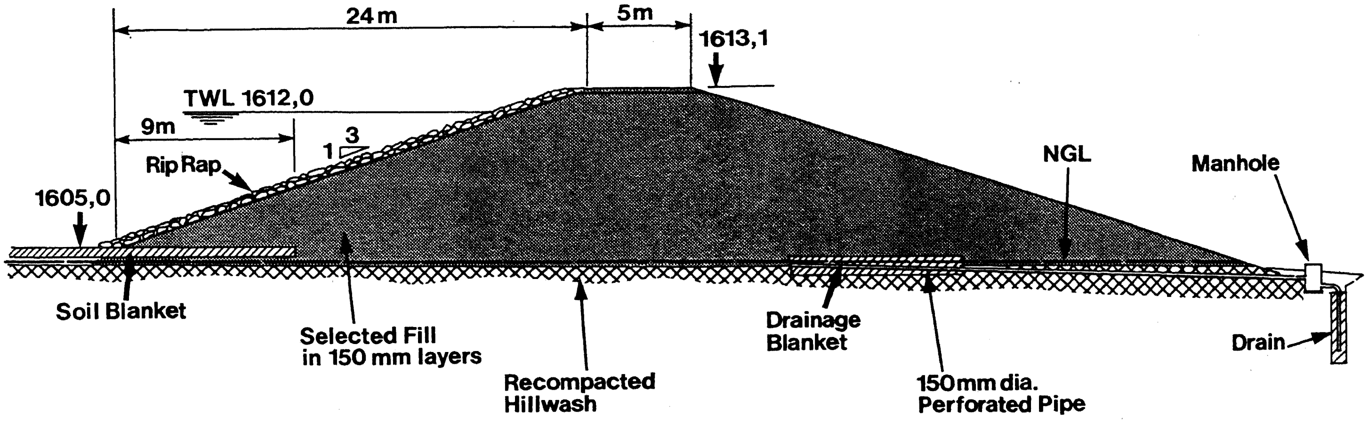

Fig. 1 Cross Section Through Perimeter Embankment

The available borrow area was located about 1.5km from the reservoir site and this provided fill for both the embankments and the soil blanket. The fill was a clayey, silty fine sand with a plasticity index in the range of 10 to 20 and a clay fraction of 11% to 25%. Laboratory testing of the fill material included permeability, compaction characteristics, total and effective shear strength parameters and potential for dispersive erosion. Following the laboratory test programme, compaction was specified as 100% Proctor at a moisture content between optimum and optimum plus 2%. The permeability at this compaction, measured in the laboratory, ranged between 2 x 10^{-8}m per second and 2 x 10^{-9} m per second. A typical result is shown in Figure 3. Minimum clay contents of 10% and 15% were specified and in view of the fact that it has been reported that laboratory measured permeabilities are lower than those pertaining to a compacted embankment, De Mèllo (1975), design permeability values of 5 x 10^{-8}m per second and 1 x 10^{-8}m per second were adopted for the embankments and floors respectively. The controls during construction were soil grading, percentage clay, moisture content and dry density.

The optimum moisture content determined by compacting samples from the borrow area to 100% Proctor compaction ranged from 12% to 14%. Maximum dry density varied from 1765 to 1900kg per m^3 with an average value of 1830kg per m^3. The soils from the borrow area were checked for their susceptibility to dispersive erosion. Both the physical pinhole test and a chemical analysis in which the quantity of dissolved sodium cations in the pore water is measured relative to other basic cations were done and these showed the materials to be non-dispersive.

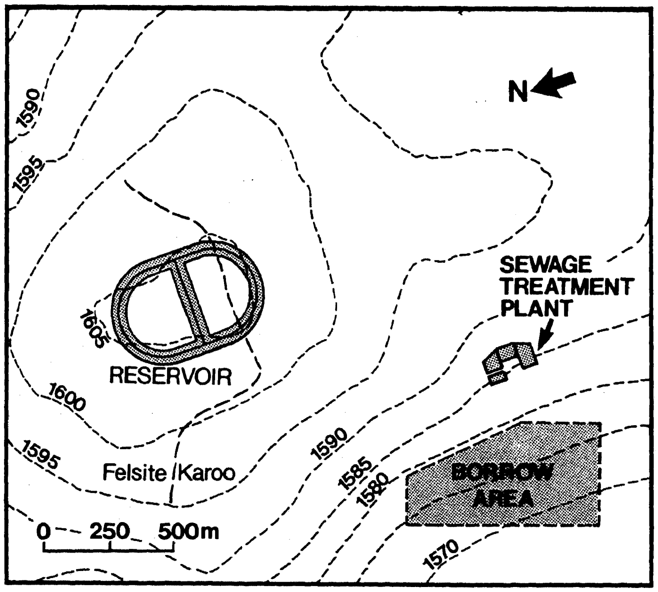

Fig. 2 Site Plan

Construction

The embankments were constructed in 150mm compacted layers and because of the potential for surface cracking of these layers each was covered by a protective soil layer immediately after compaction. Similarly the 0.5m thick soil blanket to the floors was constructed in three approximately equal layers and extends 9m within the homogeneous embankments. Each compacted layer was again covered by a protective soil layer to prevent drying out. Some 200m upslope and to the east of the borrow area is the sewage treatment plant for the installation. (Fig. 2).

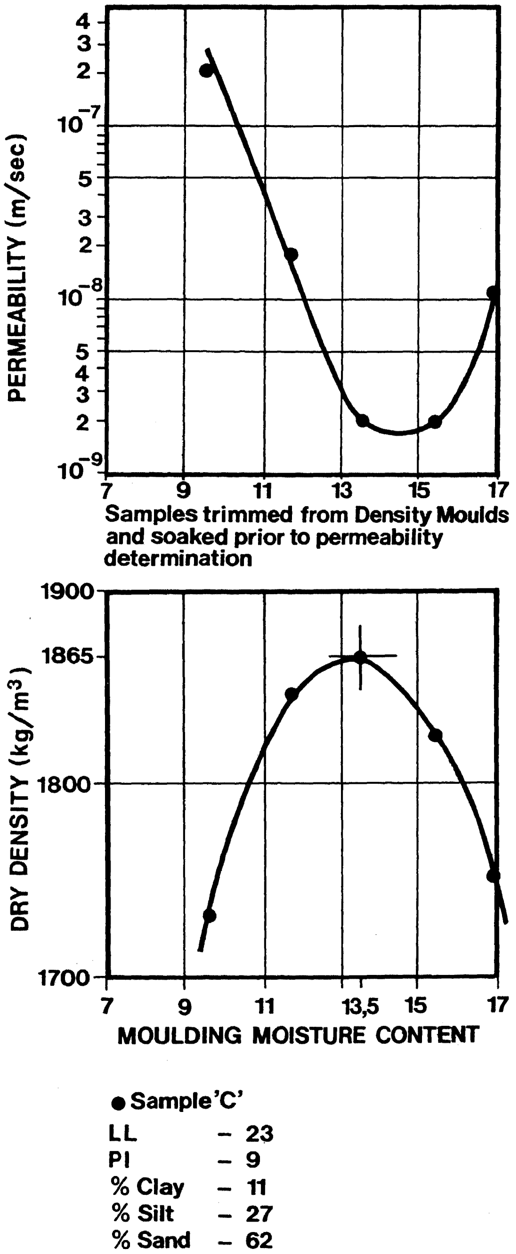

Fig. 3 Dry Density and Permeability Related to Moisture Content

This plant was overloaded during the construction period and the significance of this is two-fold. Firstly, overflow ran downslope into the region of the borrow area and secondly, the excess sewage water was available for construction purposes. Thus throughout the contract for the construction of the reservoir, this sewage effluent was used to adjust the moisture content of the soil and to maintain the protective layers moist to prevent drying out. There is a slight fall across the reservoir floors and this enabled the final layer of the floors to be compacted whilst the floor was gradually flooded.

OBSERVATIONS FOLLOWING FILLING OF THE RESERVOIR

The north compartment, was filled slowly being 8% full on 1st March, 1979 and 24% full on 21st March, 1979. During April with progressive filling of the compartment, flows from the blanket drain outlet pipes increased and wet areas were apparent around the perimeter of the embankment. Filling of both compartments ceased on 1st April, 1979 when the north compartment was 67% full.

Piezometers and standpipes were installed along two sections through the perimeter embankment for both the north and south compartments. Observations showed that water in the north compartment was flowing towards the toe through the more permeable layers of sand and gravel which lie below the emnbankment and embankment drain. Pore water pressure measurements beneath the embankment provided strong evidence of blanket leakage. Consequently, it was desirable that the blanket in the north compartment should be inspected. It was therefore proposed that all the water be transferred to the south compartment to test the soil blanket there and allow the north compartment blanket to be studied.

The change in water level in the north compartment was measured during May, 1979 when it was about 66% full using a simple stilling basin. Making allowance for evaporation and, assuming no leakage through the valves of the supply pipelines, the average water loss from the north compartment was 7.5 litres per second which is relatively little for its size.

Transfer of water from the north to the south compartments commenced on the 6th June, 1979 and equalization of the north and south compartments was complete on the 12th June. As damp patches occurred around the perimeter of the south compartment no further filling of the south compartment was carried out. The north compartment was gradually emptied and with a water depth of about 1m a number of small holes, 5mm to 6mm in diameter with bubbles of gas emerging intermittently were observed. In addition, a small mound of soil, 80mm in diameter and 10mm to 15mm high, surrounded the central hole. This evidence was subsequently destroyed by shallow water waves just prior to final emptying. Holes with a little red/brown soil, surrounding the hole, were seen against a background of grey silt which had settled out of the River water supplying the reservoir.

Samples

A sample of the gas was collected from a number of the holes in the north compartment by displacement of water from an inverted gas jar. The analysis gave Nitrogen 92%, Oxygen 7.6% and Carbon Dioxide .2%.

By comparison the percentages of the above in the atmosphere in a rural area are Nitrogen 78%, Oxygen 21%, and Carbon Dioxide .03%. It should be noted that the percentage of carbon dioxide can be higher in an industrialized area. Following emptying of the north compartment, two undisturbed block samples were cut from the soil blanket floor and their permeability and associated properties measured. Results obtained are given in Table I.

Table I

Properties of Block Samples Taken from the North Compartment after Emptying

	Block X-1	Block Y-1
Initial moisture content (%)	16.9	15.0
Initial dry density (kg/m^3)	1691	1809
Air Voids (%)	8.3	6.5
Permeability (m/sec)	$1.9\text{x}10^{-7}$	$2.1\text{x}10^{-7}$

At the measured permeability of $2 \text{ x } 10^{-7}$m per second, the blanket is ineffective in reducing water percolation. During construction four undisturbed block samples had been taken from the north compartment wall and floor. The analyses of these samples are given in Table II.

Table II

Measured Permeabilities of Block Samples Taken During Construction

Sample	Dry Density (kg/m^3)	Permeability (m/sec)
H462-Floor	1731	$1.6\text{x}10^{-7}$
H463-Floor	1923	$1.5\text{x}10^{-8}$
H464-Embankment	1931	$4.1\text{x}10^{-8}$
H465-Embankment	1828	$2.7\text{x}10^{-8}$

The area from which sample H462 was obtained was recompacted

The treated sewage effluent used for adjusting the moisture content of the material used in the construction of the earth banks and the floor lining of the reservoir was sampled in August 1979 and again in February 1980. The analyses are given in Table III.

Table III

Analysis of Effluent

	Aug 1979	Feb 1980
Chloride (mg/l as Cl)	-	52
Permanganate value (mg/l as O)	-	11
Chemical oxygen demand, COD, (mg/l)	-	120
Biochemical oxygen demand, BOD 5 days (mg/l)	-	20
Total Kjeldahl nitrogen (mg/l as N)	35	32
Ammonia (mg/l as N)	-	27
Nitrite (mg/l as N)	0.1	Nil
Nitrate (mg/l as N)	1.5	Nil
Phosphate (mg/l as P)	-	7

The February 1980 analysis is typical of an effluent produced by a heavily loaded treatment plant. The COD and BOD values are reasonably satisfactory, but there is little or no nitrification. It seems probable that the effluent used in the construction of the reservoir had a total nitrogen content (Kjeldahl, nitrite and nitrate) of around 35 mg/l.

HYPOTHESIS FOR CAUSE OF FAILURE

Most soils contain vast numbers of bacteria that are capable of oxidising nitrogen compounds to nitrite and then to nitrate. This process is known as nitrification, and is an extremely important one in nature, as most plants can utilise nitrogen only in the form of nitrate.

The nitrogen in the sewage effluent applied to the soil blanket lining consisted partly of organic nitrogen and partly of ammonia. In the soil, the organic nitrogen was converted to ammonia by various biochemical processes, referred to as deamination reactions. The ammonia produced in this way, as well as that originally present in the sewage, was oxidised initially to nitrite by a species of autotrophic bacteria, viz Nitrosomonas. The reaction can be represented as follows:

$$2NH_4^+ + 3O_2 \longrightarrow 2NO_2^- + 2H_2O + 4H^+ \qquad (1)$$

The nitrite was then transformed into nitrate by another species of autotrophic bacteria, Nitrobacter. The reaction is the following:

$$2NO_2^- + O_2 \longrightarrow 2NO_3^- \qquad (2)$$

The organisms Nitrosomonas and Nitrobacter require a lot of moisture to proliferate and a lot of oxygen to convert the ammonia into nitrite and nitrate. Both these requirements were satisfied in the loose, damp protective layer of soil, prior to being compacted. The ammonia was probably converted quantitatively into nitrate within 3 or 4 days.

In the process of filling the reservoir, soon as the floor had been covered complete with water, atmospheric oxygen could no long diffuse into the soil and the bacteria had rely exclusively on the nitrate for the oxygen supply.

As this water containing dissolved organ impurities penetrated into the floor t bacteria metabolised the dissolved organ matter, oxidising it as a source of energy an in the absence of sufficient oxygen, reduc the nitrate to nitrogen gas. It should noted that, when ammonia is oxidis biochemically it is converted to nitrate, b when nitrate is reduced biochemically it do not revert to ammonia, but to nitrogen ga Minute gas bubbles formed throughout the lay of soil penetrated, breaking down its structu completely, and allowing further penetration water, until the whole depth of the lining h been destroyed and the reservoir starte leaking.

The main evidence on which this theory is base is the fact that the gas which escaped from th floor of the reservoir and was collected belo the water surface, contained approximately 92 of nitrogen and 8% of oxygen. The presence o oxygen in the gas may have been caused b accidental contamination with air whil collecting the sample, or by the scouring o dissolved oxygen from the water by the bubble during their passage to the surface.

After the theory had been put forward, a sampl of compacted soil was taken from the reservoi embankment at a location which had not bee subject to seepage. About 4kg of this soil wa placed into a container with a perforated bas and water was allowed to percolate through it until about 0,75 litres of filtrate had bee collected. This was analysed and found t contain 16mg/l of nitrate as NO_3, whic corresponds to 3,6mg/l as N.

This test was not intended to be a quantitative one, but was aimed merely at establishing whether the compacted soil did, in fact, contain appreciable amounts of nitrate. The floor lining probably contained much more nitrate than the embankment did, as the former was constructed during the dry winter months, while the embankment was built during the rainy season, when less artificial wetting was required.

If it is assumed that the average moisture content of the material as brought in was about 8%, a further 8% was required to bring it up to the compaction moisture content of 14-16%. However, most of the soil in the floor lining probably received considerably more than this amount of sewage effluent because each protecting layer was sprayed with sewage effluent, often two or three times, to keep it moist until such time as it, in turn, was due to be compacted. It was estimated that the soil in the floor lining could have received an average of 15-20% of sewage, containing about 35mg/l of total nitrogen.

If all this was oxidised to nitrate and subsequently reduced to nitrogen gas, 5.5g of the latter would be generated in each $1m^2$ of floor. This is equivalent to 5.8 litres and is more than sufficient to alter its physical characteristics completely, and make the soil blanket lining ineffective.

Various remedial measures were considered, including a new floor lining, an internal clay cut-off wall or seepage recovery. As the reservoir was required for operational purposes, it was decided to recover the seepage collected in the perimeter drain and pump this over the embankment, thereby returning it to the reservoir.

CONCLUSIONS

The salient points may be summarized as follows:

1. The cause of the leakage was failure of the soil blanket to the floors as indicated by the piezometers.
2. Treated sewage effluent was used as construction water, being the only available source.
3. Bacteria converted the ammonia and organic nitrogen present in the construction water to nitrite and subsequently to nitrate under aerobic conditions. This was confirmed by analysis of an embankment soil sample.
4. Bacteria converted the nitrate present to nitrogen gas under anaerobic conditions, confirmed by analysis of a gas sample.
5. The gas generation which occurred within the soil blanket expanded the soil structure leading to a high water permeability as shown by the testing of block soil samples making the soil blanket ineffective in reducing percolation.

The first author was responsible for the design of the reservoir and the extensive detective work which followed the failure, although it is an unenviable task to publish a record of failure, it was felt important to draw the attention of the industry to this important phenomenon.

ACKNOWLEDGMENTS

The first author would like to acknowledge the assistance of his colleagues, particularly during the investigation stage which was a very difficult period. Special thanks go to Mr. Vosloo, who was responsible for putting forward the hypothesis described above.

REFERENCE

De Mello, V. F. B. (1975) "Some Lessons from Unsuspected Real and Fictitious Problems in Earth Dam Engineering in Brazil." Proc. 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Durban Vol. II, 285-304.