Joint Defra / EA Flood and Coastal Erosion Risk Management R&D Programme

Soil piping tests on Thorngumbald flood embankment

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Executive Summary

As part of the Defra-led Science Project FD2411 on Reducing the risk of failure of failure of flood embankments under extreme conditions, piping tests were carried out on the earthfill material taken from a flood embankment in the Humber Estuary after it had been taken out of commission. The piping tests demonstrated that internal erosion of artificially formed pipes (holes) takes place when the flow velocity through the pipe reaches a critical threshold. The hydraulic pressures and internal flow in the fill material also seem to initiate cracking soil into blocks, indicating that this may be an important failure mode for this general type of fill material under extreme flood loading.

These conclusions link and support a further more rigorous study on deterioration and failure of flood embankments though soil fissuring carried out under the collaboratively-funded UK Flood Risk Management Research Consortium (FRMRC).

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1 Introduction

A section of the flood defence embankment at Thorngumbald was to be removed in August 2003 under a managed coastal retreat programme. The Environment Agency (EA) contracted the University of Birmingham to undertake an investigation into the internal erosion (piping) potential of the embankment material from the section of the embankment that was to be removed. This investigation was undertaken in collaboration with HR Wallingford.

Three large undisturbed specimens were recovered from a section of the embankment for the purpose of undertaking piping tests at HR Wallingford. Smaller undisturbed and disturbed samples were also taken from the area immediately adjacent to the larger specimens for a laboratory investigation at the University of Birmingham.

All the specimens were recovered in August 2003 prior to removal of a section of the embankment by formed by Nuttall Ltd (contractor for the construction of the new flood defence works).

This work was an integral part of an on-going research project at the University of Birmingham, into the causes and growth of pipes in embankments, and the EC IMPACT Project (managed by HR Wallingford). This project provided a rare opportunity to sample and test real embankment material. Furthermore the timing of the event coincided with the recommendations from the EA/DEFRA Project FD2411 where the need to understand piping through embankments was identified and the EC IMPACT project, where research was being conducted into breach formation through overtopping and to a lesser extent piping. The project also coincided with the availability of facilities at HR Wallingford to undertake the tests.

This project was funded jointly by the EA and the University of Birmingham, with flume testing facilities provided by HR Wallingford. The work was completed in 2005.

2 Objectives

The main objectives of the research work were to:

i investigate and improve understanding of the pipe growth process; and

ii determine the susceptibility of the Thorngumbald embankment material to internal erosion. This was to be achieved by the following program of work:

Small-scale laboratory tests were undertaken to investigate the growth of a pipe with time. Both index and dispersion classification tests were carried out on the recovered materials. Large-scale laboratory tests were then undertaken to take account of the macro-structure of the embankment materials and to examine the relationship between laboratory tests and full-scale tests.

3 Site Location and Description

The embankment is located about 2km south east of Paull village along the north eastern bank of the river Humber estuary at OS grid reference TA 175248. A location plan is shown in Figure 1.

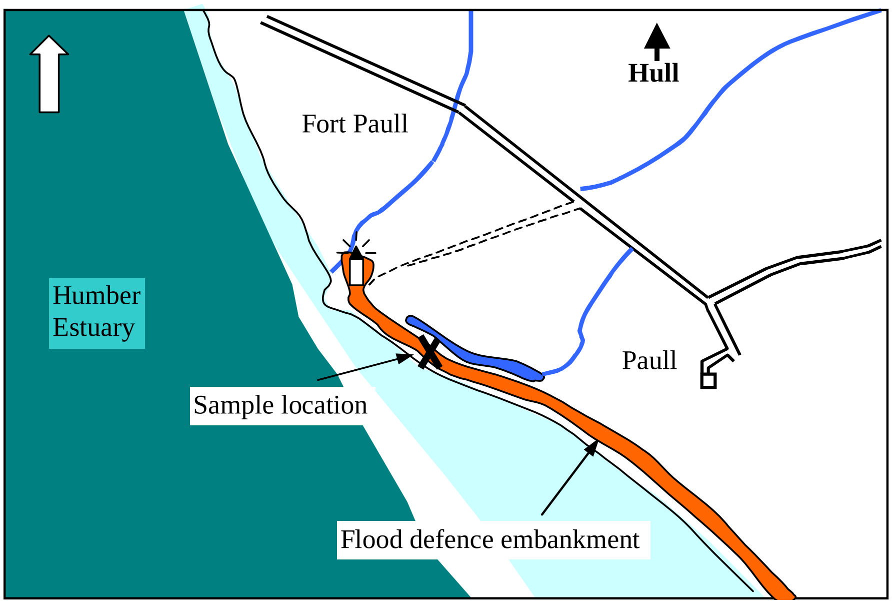


Figure 1: Location of Flood Embankment at Thorngumbald

At the test site, the crest of the embankment was about 3m above the adjacent shore level and about 3.5m above land level on the landward side. It had side slopes of about 1:3 (vertical to horizontal) and a crest width of about 3m. Pictorial views of the embankment are shown in Figure 2 and a typical section of the embankment is shown in Figure 3.

Landward embankment face Seaward embankment face

Figure 2: Views of the Embankment

Samples were obtained from the embankment from location 'x' shown on the plan in Figure 1 and in section in Figure 3. The three samples were taken from the middle of the proposed breach area from the landward side of the embankment so as not to expose the embankment to a possibility of breaching by the sea. Sampling locations are shown in Figure 3.

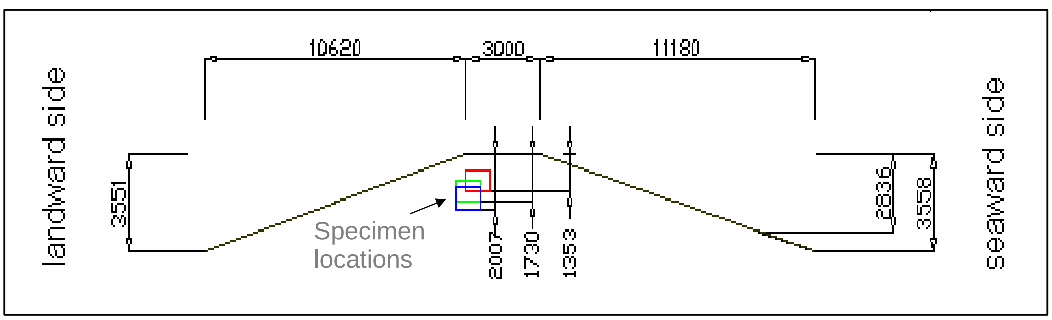


Figure 3: Location of Samples within the Embankment

The elevation of the base of the specimens in terms of 'Ordnance Datum Newlyn' (ODN) was: Specimen 1 - +4.25 m ODN, Specimen 2 - +3.87ODN and Specimen 3 - +2.79m ODN. Mean sea level and high water (spring) are approximately +0.3m ODN and +3.4m ODN respectively. Thus part of the embankment from which the lowest specimen (Specimen 3) was obtained would be subjected to some hydraulic loading. [In terms of extreme water levels, 1 year and 100 year extreme water levels (not taking account of wave height) may be as high as +4.36m ODN and 4.76mm ODN respectively. Thus embankment overtopping would occur, but, these events may of short duration.]

4 Sample Recovery

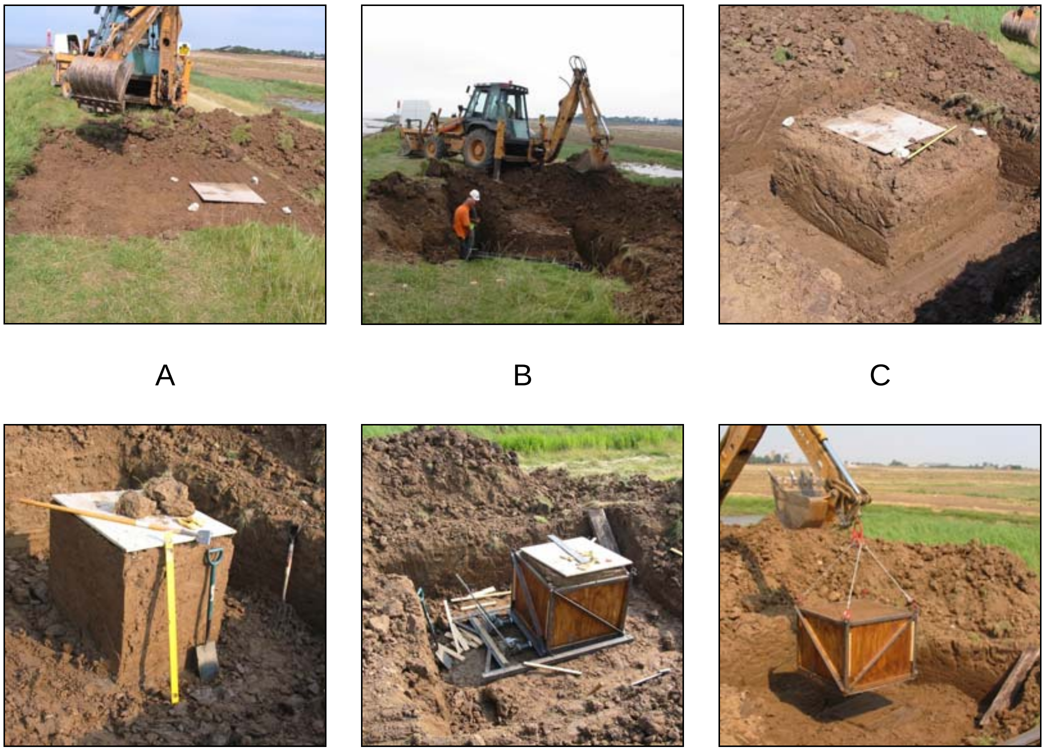
It was decided to take large enough specimens to adequately sample the macro-structure within the embankment. These specimens were also large enough so that they could be built into the available flume at HR Wallingford for piping tests.

WS Atkins undertook the structural design of the boxes for the recovery of the $0.72m^3$ specimens (0.95m x 0.95m x 0.8m high). Each box was made of a mild steel angle-iron frame with plywood walls and lid. The design permitted the front and back panels to be removed without disturbing the block of soil contained within it. The box, assembled with all the sides, was then lowered onto the trimmed block of soil. The soil block was then cut horizontally by steel plates inserted in the base. The box was then lifted out of the excavation and prepared for transportation to Wallingford for testing. Key part of the final preparation included sealing the specimens so that there would be no loss of moisture during transport and storage prior to testing.

The base of boxes numbered 1, 2 and 3 were at 1.33m, 1.73m and 2.01 m below the top of the embankment. Specimen recovery was carried out over three days during period of neap tides in August to avoid any danger of embankment breach due to overtopping.

The sampling sequence is shown pictorially in Figure 4. The location of the sample was identified and marked on the embankment surface (A). Excavator was then used to remove the surface soil to a level platform slightly above the required depth of the top of the box (B). A 1m deep trench was dug at a minimum distance of 30cm (C) from the edge of the sample. This then allowed the sample to be trimmed to fit the inside size of the box (D). The box was then lowered over the sample and allowed to sit on the base of the trench with approximately 20cm of sample proud of the top of the box. A specially designed jacking system was then attached to the base which enabled insertion of metal cutting plates into the base of the box and thus cut the sample at the base (E). The top was then trimmed and the excavator was then used was then used to hoist the boxed sample from the excavation pit (F). Dry sand was poured into any cavities that remained between the sampling box and sides of the specimen before attaching the lid. The lid was sealed to prevent loss of moisture. The recovered specimens were placed on a 20mm thick rubber layer during transportation to Wallingford.

During the recovery of larger specimens, fifteen 38mm diameter, six 100mm diameter undisturbed and a number of bag samples (disturbed specimens) were obtained for the laboratory investigation.



A B C

D E F

Figure 4: Recovery Method for Embankment Samples

During specimen recovery, it was found that up to a depth of about 1.3m, upper layer of the embankment comprised blocky, firm to stiff, brown silty clay with some voids and sometimes approximately orthogonal fissures resulting in small blocks of soil. The degree of fissuring was variable both on plan and with depth. The largest voids were about 20mm wide and were discontinuous. In general, fissuring and the degree of voids decreased with depth. As such deeper specimen comprised of more homogeneous material, with a fewer voids and fissures. It is possible that the embankment was formed without adequate compaction and it is most likely that the lower parts were compacted due to overburden pressure.

5 Properties of the Embankment Soil

Laboratory tests were conducted to determine the optimum moisture content of the material together with the dry density. This enabled a comparison to be made between the in-situ density (measured from the undisturbed specimens) and the maximum dry density (determined using both heavy and light compaction tests). The compaction tests were undertaken in accordance with the BS1377:1990. Both Liquid Limit and Plastic Limit and Shrinkage Limit determinations were also made. Permeability of the recovered samples was also determined in accordance with the BS1377:1990. The results of moisture content, Liquid and Plastic Limit and Shrinkage Limit determinations, together with permeability are summarised in Table 1. Shear strength was determined by conducting hand vane tests, in accordance with BS1377:1990.

Previous research (Arulanandan *et al*., 1975) has shown that salt content, in particular the sodium salt to total salt ratio of the soil, may have a significant effect on the erodibility of soils. Therefore, total salt and sodium salt content determinations were made. These results summarised in Figure 5, show that the Thorngumbald material was on the boundary between dispersive and non-dispersive clays based on the recommendations by Sherard *et al.* (1976). Atomic absorption technique was used to determine the salt content by measuring the concentrations of ions in the pore water extract. Sodium, potassium, magnesium and calcium ions were the four most abundant and the sum of their concentrations was considered to make up the total dissolved salt concentration.

Box No.	1	2	3
Natural Moisture (%)	24	27	24
Dry Density (g/cm^3)	1.42	1.39	1.42
Bulk Density (g/cm^3)	1.76	1.77	1.76
Specific Gravity (g/cm^3)	2.64	2.65	2.63
Plastic Limit (%)	22	21	23
Liquid Limit (%)	45	42	45
Shear Strength (kPa)	56	52	58
Permeability (m/s)	2×10^{-5}	2×10^{-5}	2×10^{-5}
Shrinkage (%)	11	10	10

Moisture content determinations shown are average values for each box

Table 1: Properties of the Embankment Material

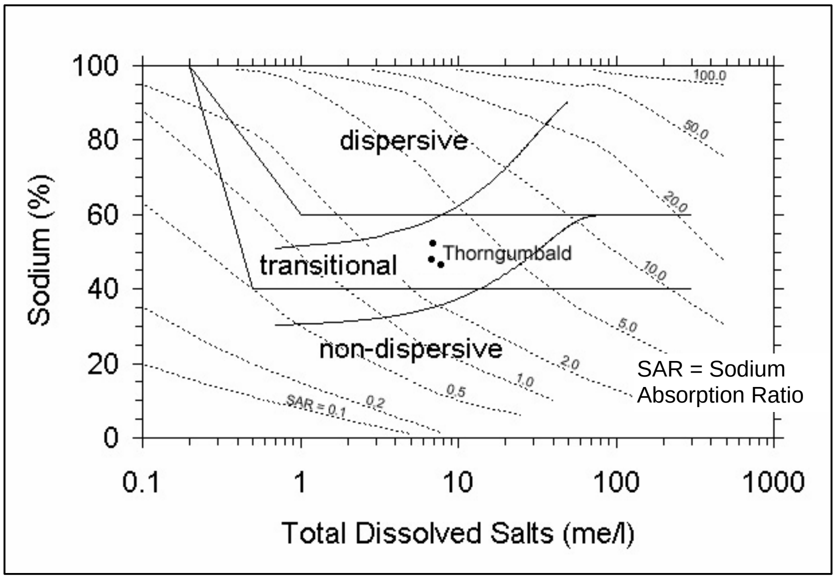


Figure 5: Dispersive character of the Thorngumbald Clay Based on Sodium Absorption Ratio (*after Sherard et al., 1976*)

Activity of a soil is the ratio of its Plasticity Index (Liquid Limit – Plastic Limit) and the clay content and can be used to assess susceptibility of a soil to piping (Resendiz, 1977). Plasticity Index and percentage clay fines for the Thorngumbald embankment clay, shown in Figure 6, suggest that it is susceptible to piping.

Moisture content distribution in the embankment with depth is shown in Figure 7. Although there was an overlap in the depths from which samples were taken, there was up to 3% difference in moisture content from similar elevations. The reduced moisture content of the mid-depth specimens for each of the specimens is thought to be a coincidence and reflects variability within the embankment.

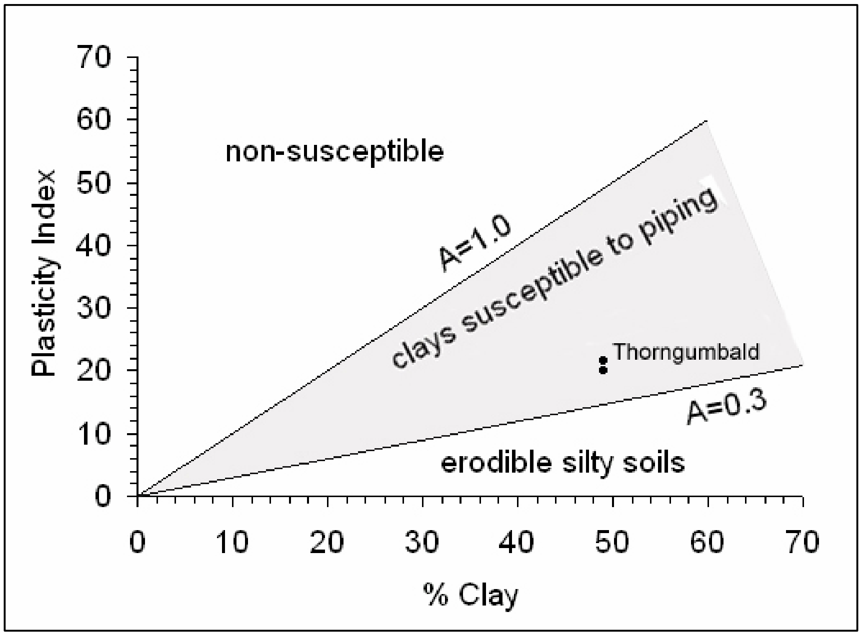


Figure 6: Clay Activity and Susceptibility to Piping (Resendiz, 1977)

A comparison of measured density and density determined from compaction tests (both heavy and light) is shown in Figure 8. The dry density of the embankment material was about 15% and 22% lower than the maximum dry density measured in the laboratory investigation for both the light and heavy compactions respectively. However, the field moisture content was about 6% and 10% respectively higher than the optimum moisture content determined respectively from the light and heavy compaction tests. At the higher moisture contents measured in the field it is estimated that the dry density of the in-place embankment material was only about 5% to 7% below that determined from both the compaction tests. It is not possible to comment on the implications of this without knowing the design to which the embankment was constructed. [It has clearly been stable for numerous decades. So perhaps it has met its requirements in terms of strength.] It is however worth noting that the field moisture contents were higher than the optimum moisture contents ascertained from compaction tests and the field density was much lower than the maximum dry density. Thus it is not possible to pin down the cause of fissuring since in each case moisture content was higher than the Plastic Limit of the soil. The field density was considered to be particularly low for a long standing flood embankment. Many such embankments are known to be constructed with relatively poor quality control by modern standards.

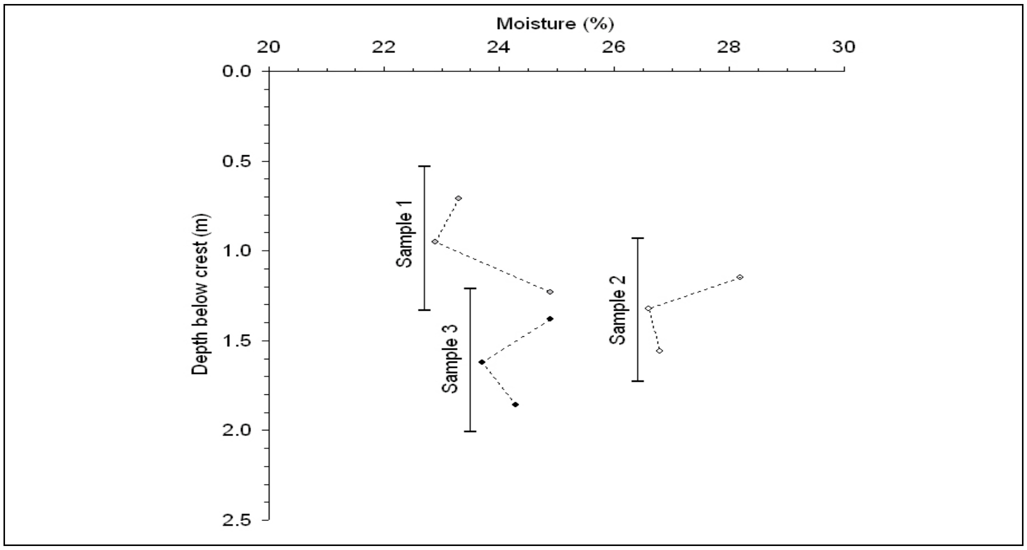


Figure 7: Variation of Natural Moisture Content with Height

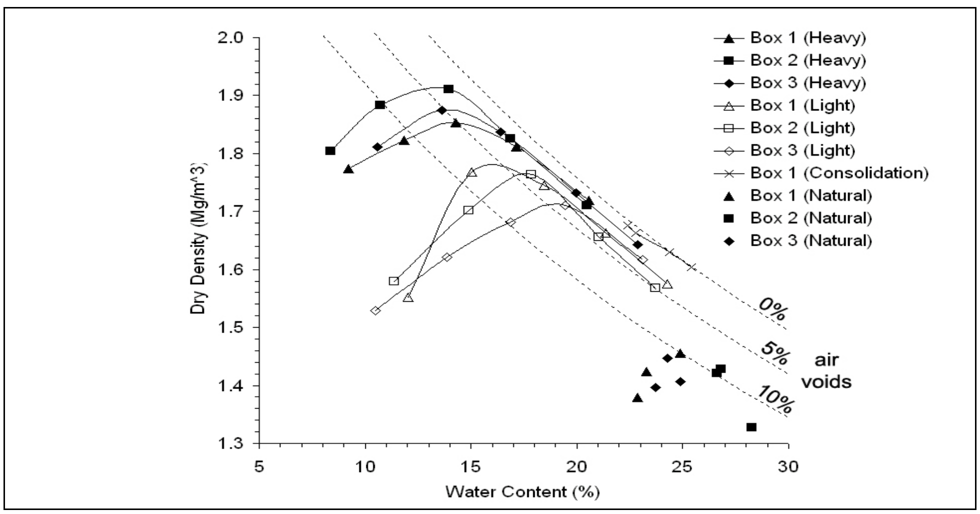


Figure 8: Compaction Characteristics

[In Figure 3, "Heavy" refers to method of compaction using a 4.5 kg rammer, "Light" refers to method of compaction that uses 2.5 kg rammer, "Consolidation" refers to specimens consolidated from slurry and "Natural" refers to density of material in its natural state in the embankment]

For the laboratory pipe erosion tests, specimens were reconstituted from slurry made from the recovered specimens. The densities achieved for these tests are also shown as "Box 1 (consolidated)" in Figure 8. Field densities were about 10% lower than those of the reconstituted specimens. Lower densities were expected since the in situ embankment material contained many voids.

Since the in-place material was at high moisture content, it was expected to have lower swelling compared to that which may occur for soil compacted at lower moisture content. Upon wetting the in-place material would therefore not absorb much more water.

6 Laboratory Internal Erosion Tests

The internal erosion test measures the amount of erosion that takes place through a pre-formed conduit in a soil sample. The flow rate applied to the sample is recorded along with the amount and chemical composition of the eroded material. The erosion rate can be calculated and the growth of the induced pipe can be determined.

The erodibility of a soil is controlled by two factors, the strength of the soil, in terms of erosion resistance, and the flow regime of the eroding fluid. Internal erosion of soils is greatly assisted by the presence of dispersive clays. The internal erosion test was therefore used to investigate these factors.

The pinhole test is used to classify the dispersibility of a soil (Sherard *et al*., 1992). A modified pinhole test, developed by Burns (2004), where flow rate was measured together with the amount of material eroded, was conducted on Thorngumbald material. The internal erosion test apparatus is shown in Figure 9. Internal erosion test specimens were 60mm long with a diameter of 38mm and the initial pipe diameter was 1 mm. The pinholes were made with a syringe needle, which was pushed into a specimen using a guide former.

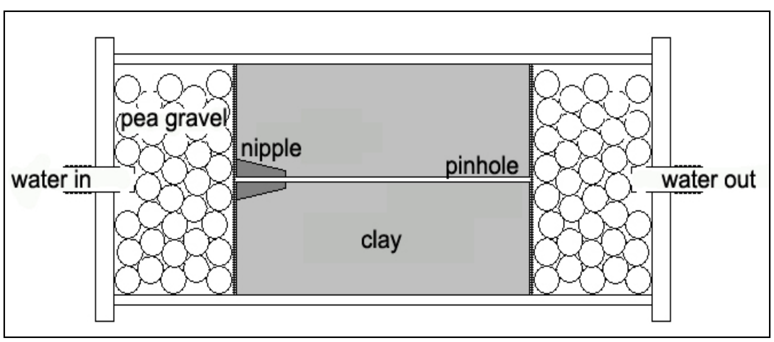


Figure 9: Internal Erosion Test Apparatus

Fourteen pipe tests were conducted on undisturbed specimens for a range of flow rates for selected durations. The amount of material eroded was monitored. The volumetric discharge and hydraulic gradients used in the laboratory tests are shown in Table 2.

Discharge (ml/min)	100	150	200	250
Hydraulic Gradient	3.8	9.7	15.2	31.2

Table 2 Hydraulic gradients and flow used for laboratory tests.

A resin cast of the eroded void was obtained for each test. The resin cast was then digitised in three dimensions and the volume of the eroded material was calculated. Eroded shapes of the pipes formed for different flow rates and for 50, 100 and 200 minute duration are shown in Figure 10 (black colour shows a typical cross-section of the shape of eroded volume.

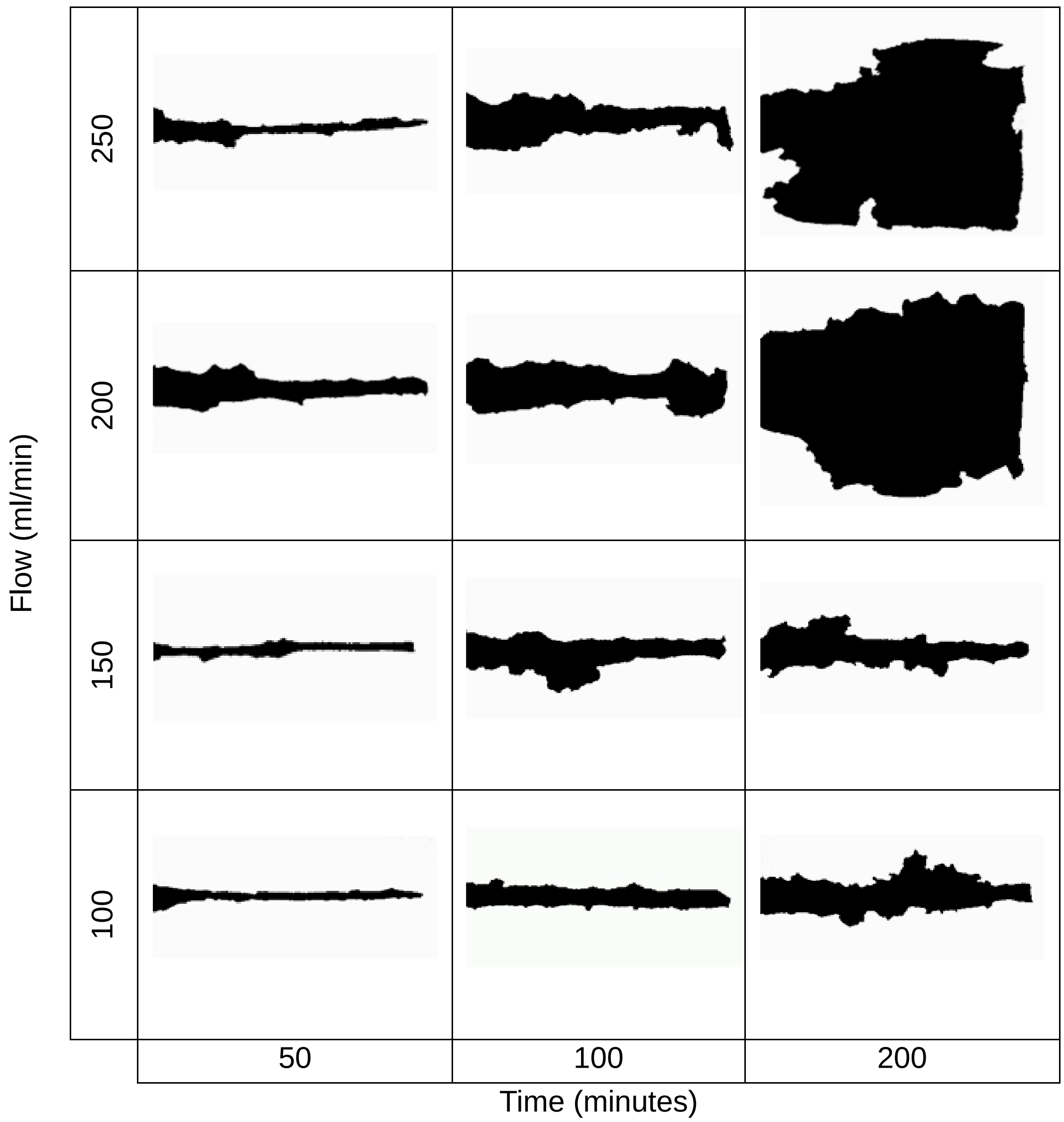


Figure 10. Cross-sections of Eroded Shapes from Internal Erosion Test Arising at a Range of Times for a Range of Flow Rates for Tests on Specimens Compacted at the Field Density.

The rate of erosion of re-formed Thorngumbald clay (at its natural moisture content and density) against time of applied flow is shown in Figure 11. The erosion rate is normalised in terms of volume of material eroded (g) per unit length (cm) of the pipe. For flow rates of below 150ml/min and below there was no significant erosion, suggesting formation of a stable pipe. For flow of greater than 200ml/minute there was a rapid increase in erosion after about 100minutes. For lesser period the pipe seems to be stable. This perhaps suggests that excessive exposure to high flow rate may lead to increased shear stress on the particles, which lead to their dislodgement. Once particles start to dislodge, turbulent flow may develop that may lead to very rapid increase in erosion. This excessive erosion can be seen in Figure 10 flow above 200ml/minute for duration of 200 minutes.

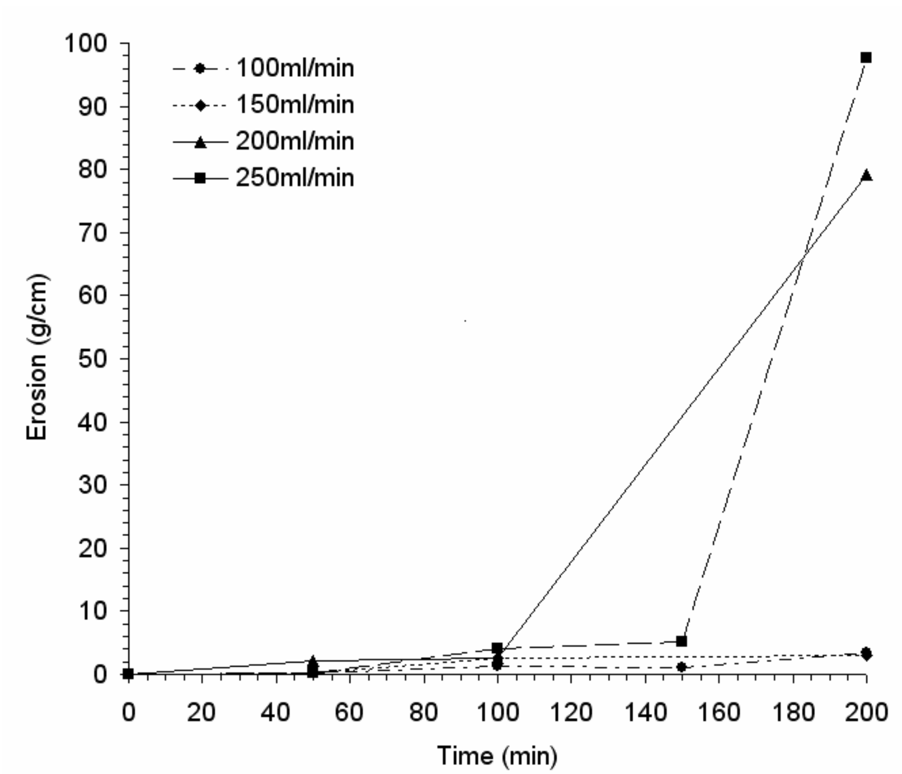


Figure 11: Internal Erosion Rates for Thorngumbald Clay (at its natural moisture content and density) Against Time of Applied Flow

7 Tests on Large Specimens at HR Wallingford

These tests were carried out in order to assess the growth of a pre-formed pipe in the *undisturbed* embankment material. In order to do this it was necessary to take as large a sample a possible in order to capture the macro-structure of soil. Procedures for conducting the tests and their results are described in this section.

The material from the three large samples exhibited similar characteristics with Liquid Limit of 22% and Plastic Limit of 44%, and moisture content of 25%.

The flume chosen for this study could give a head of water of approximately 95cm, which would produce a hydraulic gradient of approximately 1 across the sample. A large flume reservoir was required in order to produce a constant head during pipe growth or failure of the sample, where the discharge may increase rapidly. A rapid increase in outflow discharge would decrease the static head of water in front of the sample, so a weir system was used. This allowed a constant head of water to be achieved while water was being constantly pumped from the sump to the flume. It also meant that if the outflow discharge increased significantly, there would be a relatively small drop in head, as the outflow would be compensated by the pumping in rate. However, if the outflow discharge became significantly greater than the pump discharge then there would be a drop in head. Approximately 70 cubic meters of water was held behind the sample in the flume. This large volume of water provided some technical problems of providing an instantaneous start to the test. It was decided that the head of water supplied to the sample would be gradually increased to full head over the period of filling of the flume. The water level on the downstream side of the sample was kept at approximately 10mm above the flume floor. This provided the greatest head drop across the sample. The sample set up is shown in section in Figure 12, in plan in Figure 13, and pictorially in Figure 14.

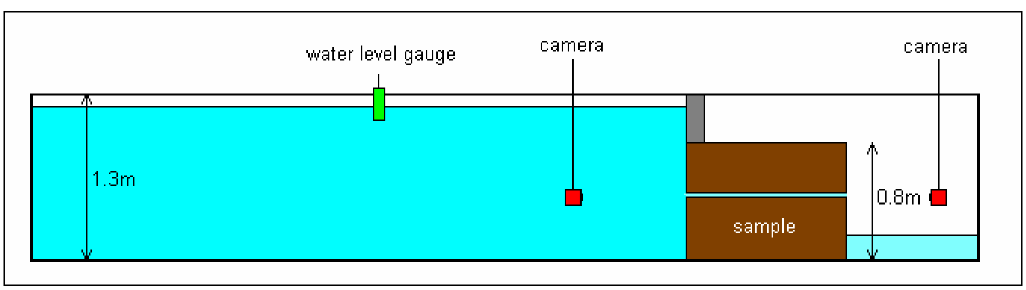


Figure 12: Section of the Flume

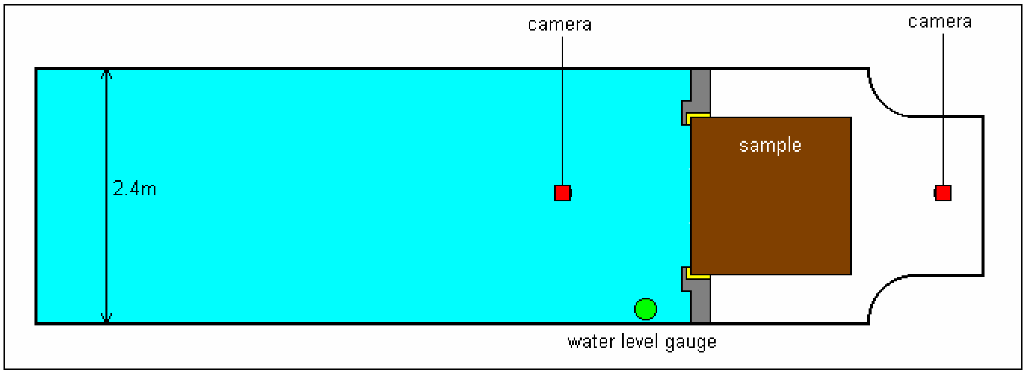


Figure 13: Plan of the Flume

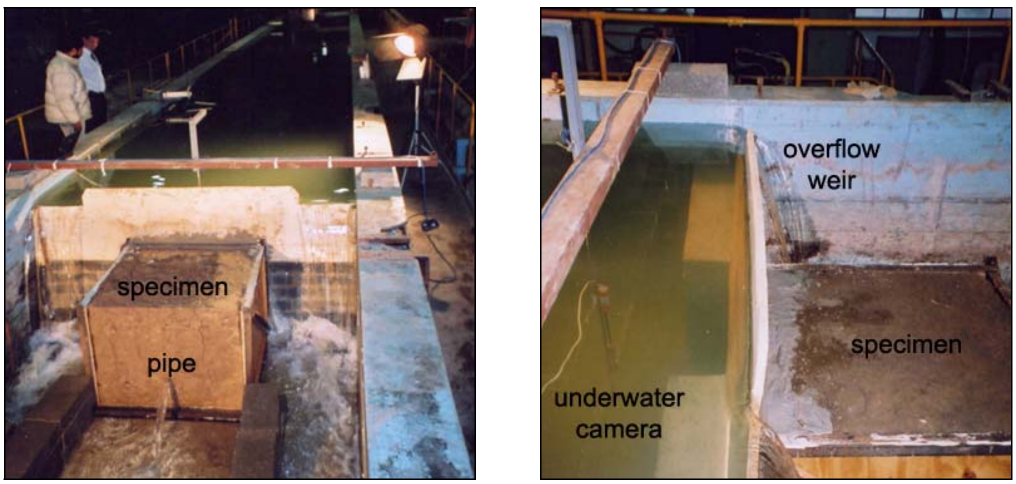


Figure 14: The Flume

The flume was 2.4m wide and a block-work wall was erected to reduce the size so that the specimens could be set up. In order to get the full head of water a plywood cut-off wall was also erected above the specimens. The front and rear panels of the box were removed and a seal was formed between the specimen and the block-work. A hole was bored through the specimen at 300mm above the base of the specimen. These holes were formed using wood-boring augers of 20, 34, or 50mm diameter.

An underwater camera was then mounted about 0.5m upstream of the inlet to the pipe. Digital cameras were used to monitor the downstream face of the pipe. Water specimens were also obtained at different time intervals to enable assessment of the rate of erosion to be made.

A Crump weir installed downstream of the sample was used to measure discharge and together with the calculated flow values of the side weirs the discharge through the pipe was calculated. Ultrasonic sensors were used to measure the water level at various points around the flume and were used to calculate the head of water and discharge.

7.1 Test 1

Pipe Diameter: 20mm

Head of water: 910mm

The first sample to be tested was Box 1, which was taken near to the top of the embankment with its base being at 1.33m for the embankment crest. Test 1 was run twice due to complications. The upstream water level and discharge through the pipe against pipe are shown Figure 15. The results show that the upstream head of water was not constant. This was because during the first run a major leak appeared in the side of the flume, just as peak water level was achieved. The test therefore had to be abandoned so that repairs could be carried out. The second run also ran into difficulties shortly after peak water level was reached. This time large leakage was observed between the upstream face and the weir. It was not possible to control this leakage and the force to the water caused the soil block to be moved out from within the box. The test was abandoned, as the specimen was unusable. The upstream and downstream faces of the sample block are shown in Figures 16 and 17 respectively. Over the 22 minutes of variable head, both the upstream and downstream faces of the pipe did not show signs of erosion.

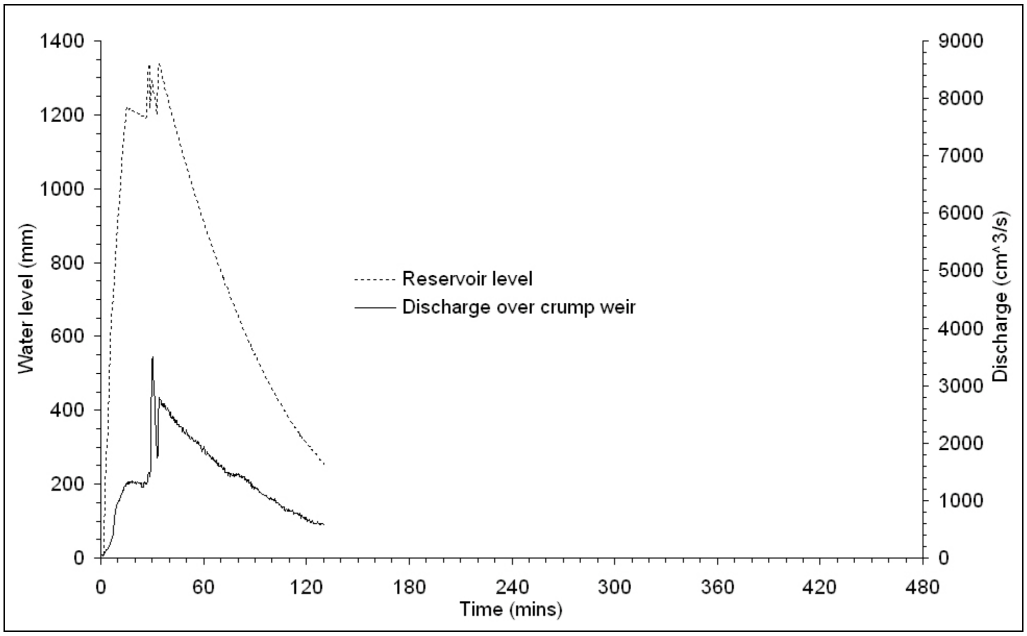


Figure 15: Water Level and Discharge Hydrograph for Pipe Test No. 1

Test abandoned

00:04:00	00:10:00	00:22:00	00:35:00

Figure 16: Upstream Face for Test No. 1

Test abandoned

00:04:00	00:10:00	00:22:00	00:35:00

Figure 17: Downstream Face for Test No. 1

7.2 Test 2

Pipe diameter: 34mm

Head of water: 910mm

Test 2 used the sample from Box 2. The sample was inspected before the start of the test and a crack was noticed along the top and continuing down the downstream face. The degree to which this crack developed during transport or simply reflected a wider existing network of fissures within the sample was unclear. Given the care taken to transport undisturbed samples, it is thought more likely to reflect an existing fault or fissure line within the sample. At the beginning of the test the crack was estimated to be approximately 1mm in width, but it was not possible to ascertain its depth. During the test this crack was monitored. Under cutting of the downstream face was also observed and approximately 38 minutes after start of the test a small block failure occurred essentially below the level of the pipe (see second photograph in Figure 20) This was considered to have occurred due to ingress of water into fissures in the sample. Subsequent to this failure, the vertical crack started to widen and large block failure of the downstream face occurred about 58 minutes after the start of the test. The presence of voids and fissures are considered to have been the main cause of block failures.

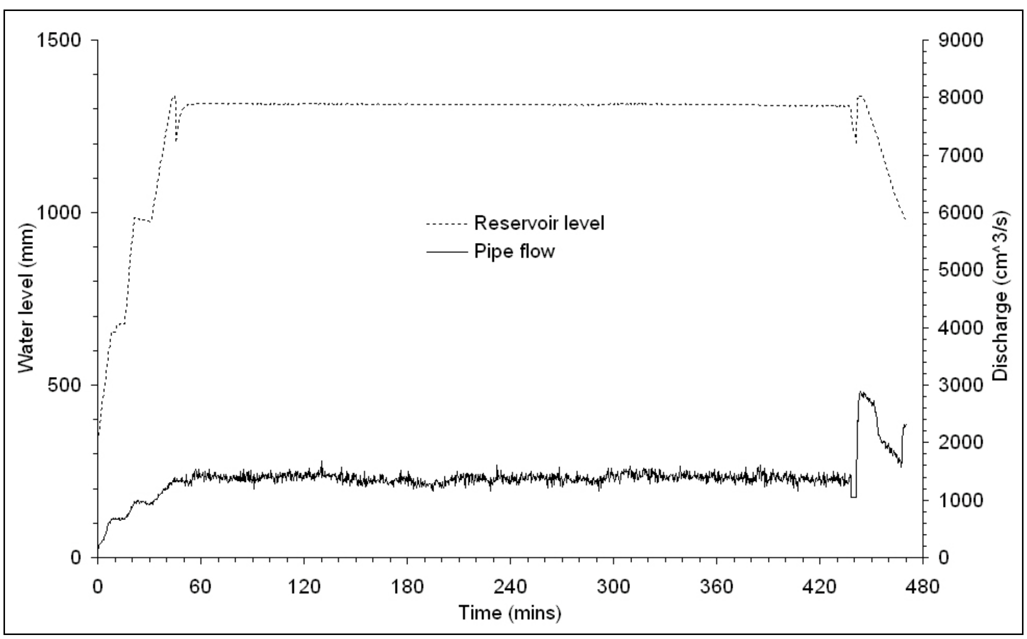


Figure 18: Water Level and Discharge Hydrograph for Pipe Test No. 2

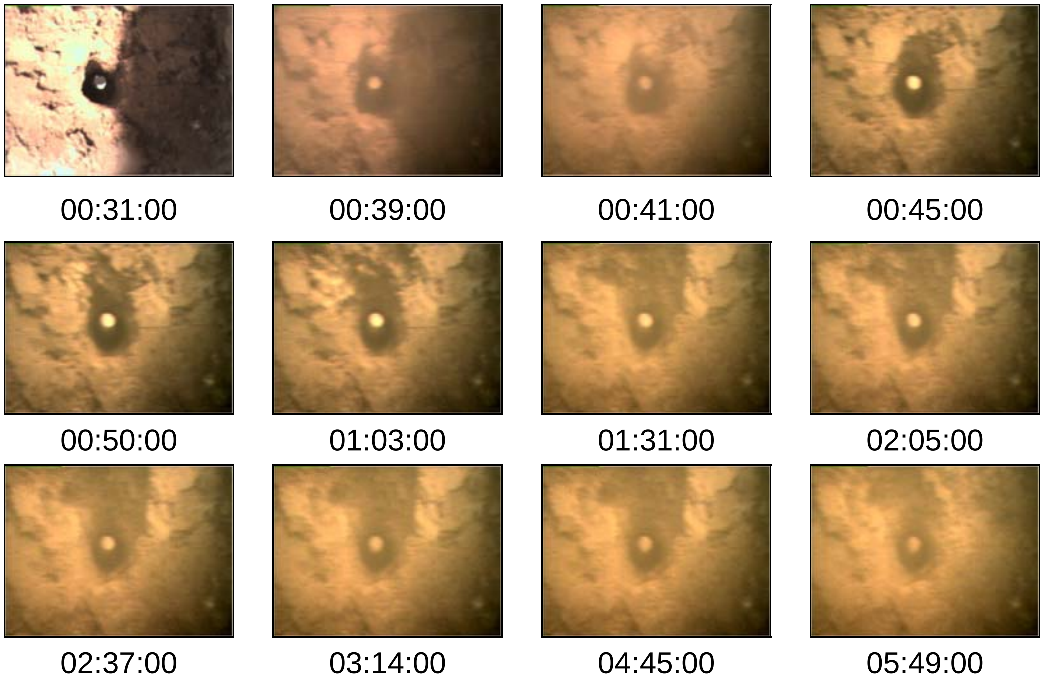


Figure 19: Upstream Face for Test No. 2

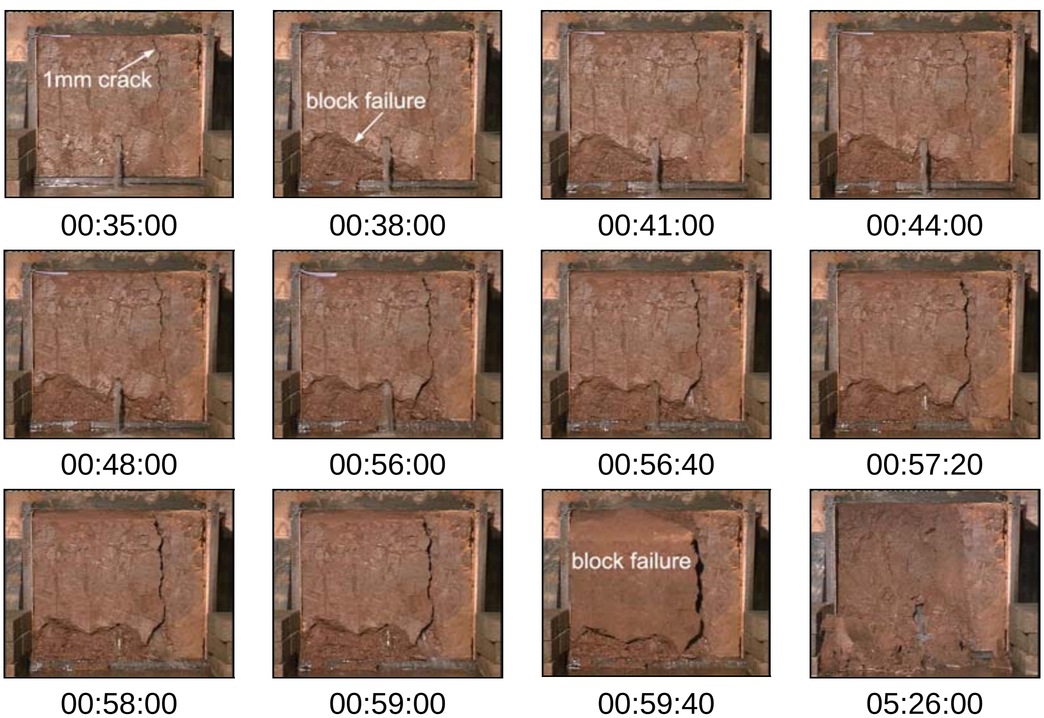


Figure 20: Downstream Face for Test No. 2

After this the test was run for a further 6 hours with no notable signs of block failure or significant erosion occurring. The upstream water level and discharge through the pipe are shown Figure 18. The upstream and downstream faces of the test specimen are shown in Figures 19 and 20.

7.3 Test 3

Pipe diameter: 50mm

Head of water: 920mm

Box 3 was used for this test. The sample was the deepest of the three with its base at 2.01m below the crest. Erosion was again seen below the level of the pipe outlet. In this case erosion was directly under the outlet and then spread to either side. There was also some erosion above the outlet and into the specimen along the roof of the pipe to a distance of approximately 180mm into the specimen. Approximately 2 hours after the start of the test a large block failure occurred on the downstream face. Increased seepage was noted in the area of the crack. After approximately 5 hours, another large block failure occurred on the opposite side of the previous failure. This caused material on the roof of the pipe to fail. The upstream water level and discharge through the pipe are shown Figure 21. The upstream and downstream faces of the test specimen are shown in Figures 22 and 23 respectively. It was clear in this instance that voids and fissures were the main contributing factors.

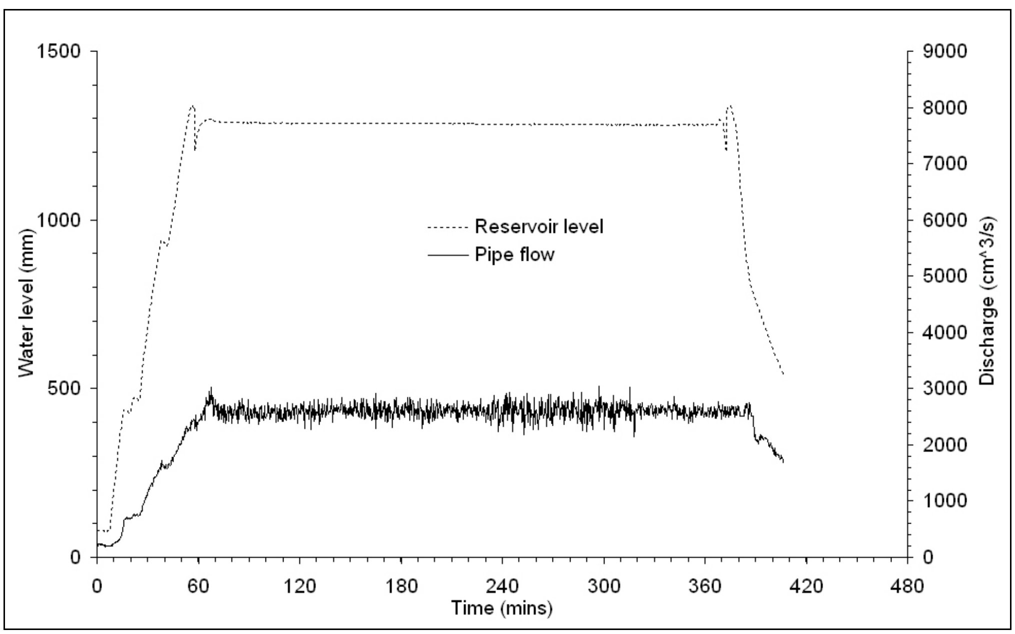


Figure 21: Water Level and Discharge Hydrograph for Pipe Test No. 3

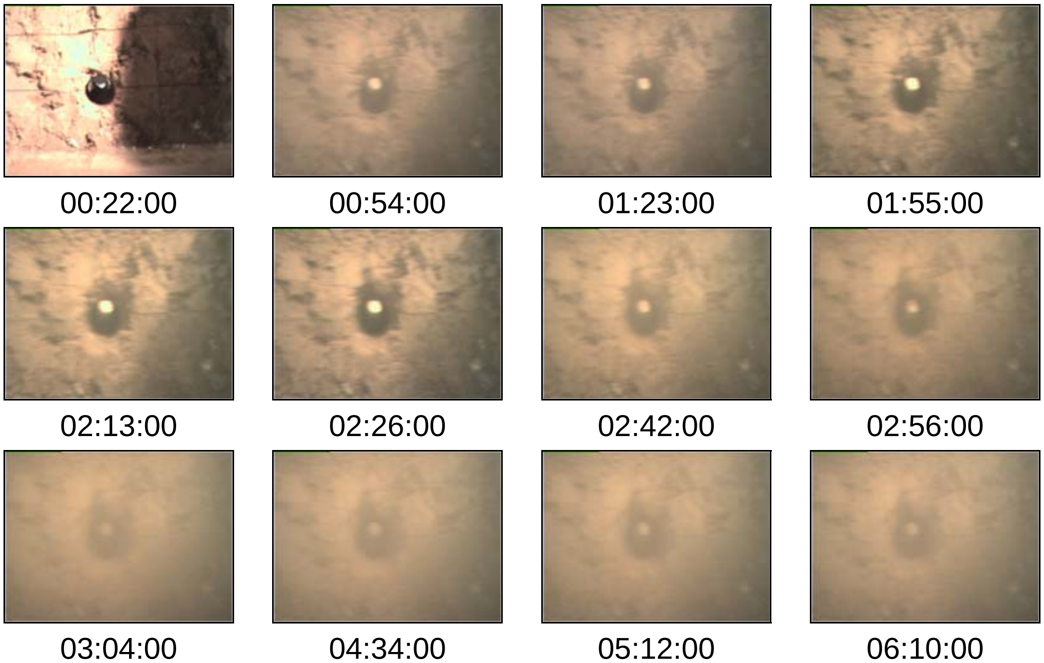


Figure 22: Upstream Face for Test No. 3

Figure 23: Downstream Face for Test No. 3

8 General Discussion

In the flume, the only parameter that could be varied was the pipe diameter as the head of water was restricted by the size of the flume. However, in the laboratory tests the pipe diameter was kept constant and the discharge was varied using a flow meter at a corresponding hydraulic gradient. The intake hydraulic gradient applied to the large scale test was approximately 0.95 whilst for the laboratory tests it ranged from 3.8 to 31.2. In the large scale tests, at a hydraulic gradient of 0.95, no internal erosion was observed.

The relationship between initial velocity in the pipe and erosion per unit length for the small scale are shown in Figure 24. Results show that there was little erosion below an initial velocity of about 3.2m/s. Erosion increased rapidly beyond this velocity.

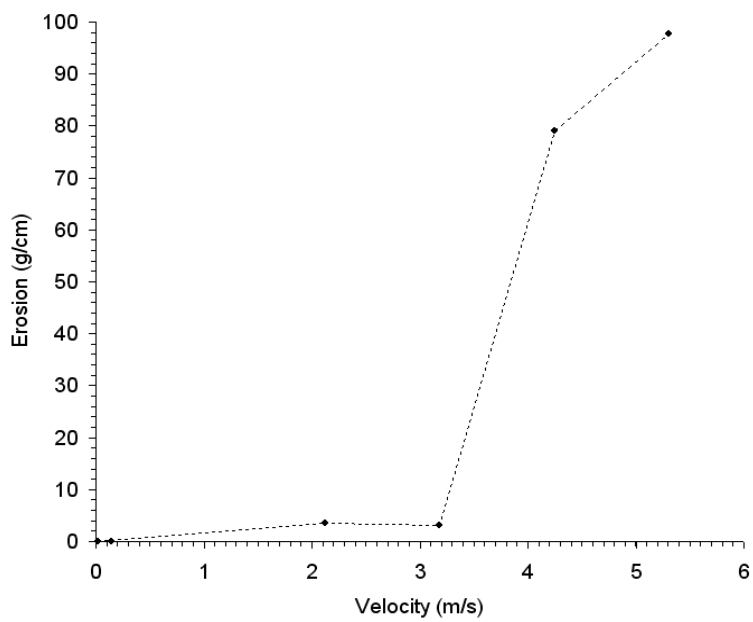


Figure 24. Erosion of embankment clay at 200 minutes in terms of initial velocity.

Results of all the tests in terms of pipe diameter, discharge, hydraulic head (hi), initial velocity and erosion in terms of unit length of pipe are given in Table 3. Whilst there is no overlap between the discharge rates, it seems that velocity is the key variable in terms of erosion. Thus, in this instance, it is tentatively suggested that provided the velocity of flow can be limited to below about 3.2m/s a stable pipe may exit provided also that failure due to other modes is not initiated.

Test	Pipe dia. (mm)	Discharge (ml/min)	hi (m/m)	Velocity (m/s)	Erosion (g/cm)
flume	20	2800	0.96	0.15	na
flume	34	1400	0.96	0.03	0
flume	50	2800	0.97	0.02	0
laboratory	1	100	3.80	2.12	3.47
laboratory	1	150	9.70	3.18	3.07
laboratory	1	200	15.20	4.24	79.13
laboratory	1	250	31.20	5.31	97.66

Table 3. Summary of Results from both Laboratory and Flume Pipe Tests.

9 Conclusions

The following conclusions were drawn from this investigation.

The classification tests suggested the clay from the embankment was marginal in terms of erodibility.

The embankment is constructed from “poorly” compacted material as it has a dry density that was at least 15% lower than maximum dry density ascertained from laboratory compaction tests. The in situ moisture content of the soil was also about 6% greater than that determined from a laboratory compaction test.

Results of laboratory based internal erosion tests (pinhole test) suggested that high erosion could take place if the flow rate through the standard induced pipe was greater than about 200ml/min (velocity 4.2 m/s) for prolonged period.

Results thus suggest that flow rate and time may both be the important factors in affecting the amount of erosion that takes place since, increased flow results in increase in the amount of erosion and for a given flow rate, the amount of material eroded increases with time. Tests on larger block specimens suggested that block failure induced by crack growth through the downstream face may be the main mechanism of failure .

The results of this study have shown that the Thorngumbald material is poorly compacted with many voids and fissures, and that initially a “block type” mode of failure is likely. Under this failure mode, the voids and fissures are acting as a conduit for the ingress and flow of water, subsequently destabilising and allowing the removal of soil blocks, rather than the uniform and progressive erosion of soil within a pipe.

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