Lessons from incidents and geotechnical investigations at embankment dams

- CIRIA dam incident guide
- Origin of BRE's research work on embankment dams
- Field investigations and incidents
  1. Reservoir drawdown deformations
  2. Stress measurement in cores, hydraulic fracture and internal erosion - Greenbooth Investigation
  3. Internal erosion and conduits

Andrew Charles (BRE)
Paul Tedd (BRE)
Alan Warren (Motts)

BDS Meeting Offer

£ 40 non members

£ 30 members

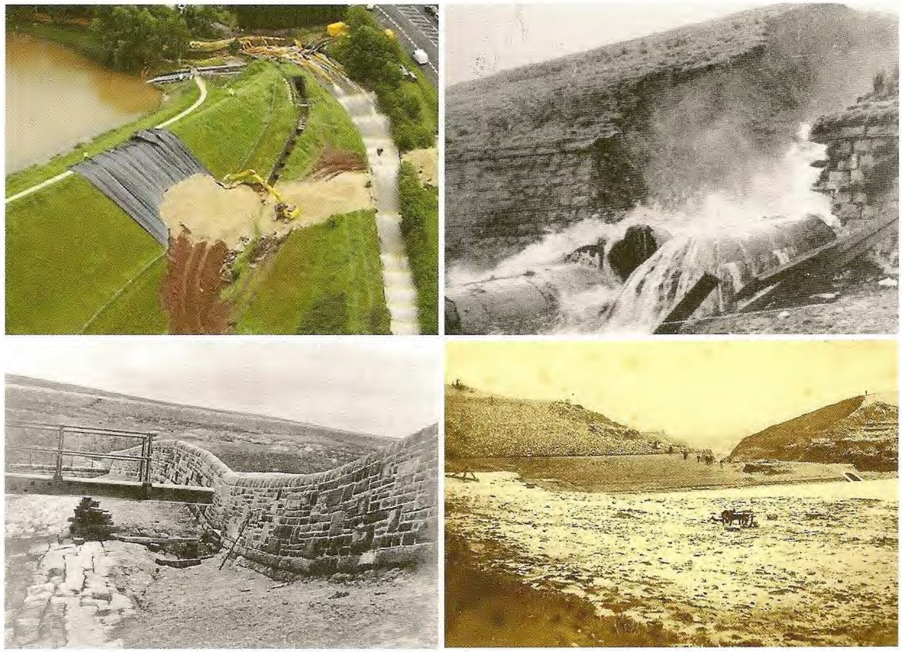
Usual price

£60 CIRIA member

£120 Non member

ciria

Lessons from incidents at dams and reservoirs - an engineering guide



Origins of the Incident report

- 1975 - Moffat publishes list of incidents in 1st BNCOLD Conference
- 1985 - Charles and others at BRE publish case histories and sets up National Dams Database
- 2004 - Database transferred to Environment Agency
- 2008 - EA commissioned BRE and Halcrows to write incident report.
- 2010 - Completed and put on EA website
- 2012 - CIRIA agree to produce updated much improved hard copy
- June 2014 - Published

Sponsors of the CIRIA Guide

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Structure of the CIRIA Guide

- Part 1: Dam incidents and reservoir safety: learning from British experience over the last two hundred years 30 pages
- Part 2: Description of incidents at British dams and reservoirs (102 incidents, 110 pages)
- Part 3: Description of incidents at Overseas dams and reservoirs (20 incidents, 20 pages)
- Length 167 pages plus 17 pages of references

Part 1

- It provides a historical overview of the subject demonstrating how serious incidents have improved our understanding of dam behaviour and the hazards posed by these structures.
- It also shows the close links between historical incidents and failures, and the development of reservoir safety legislation and guidance.

Introduction

- “The history of dam building, since the dawn of civilisation, is a long series of failures. Man learns little from success, but a lot from failure. Not to publish the facts about failure, and we all know many reasons not to do so, is a severe breach of our duties as engineers”

  Londe P (1980). Lessons from earth dam failures. Proc of symposium on geotechnical problems and practice of dam engineering, Bangkok

Timeline of failures and developments

Failures	Date	Developments, legislation
Failure of Bilberry, 81 deaths	1852	Zoned fill construction become common practice
Failure of Dale Dyke, 244 deaths	1864	Introduction of Waterworks Bill in 1866
Cwm Carne, 12 deaths	1875	None
Dolgarrog failure, 16 deaths	1925	Led to Reservoirs (Safety Provisions) Act 1930.
Warmwithens failure	1970	
	1975	Res. Act, 1975. Flood studies report.
Construction failure at Carsington	1984	Instigation of review panels for dam construction

Part 2: Description of incidents at British dams and reservoirs

Grouped by:

1 to 3: Internal erosion

4: Incidents due to pipe or valve failure

5 & 6: Slope instability during construction in-service

7: External erosion due to flood flow

8: Wave damage to upstream protection

10: Concrete and masonry dams

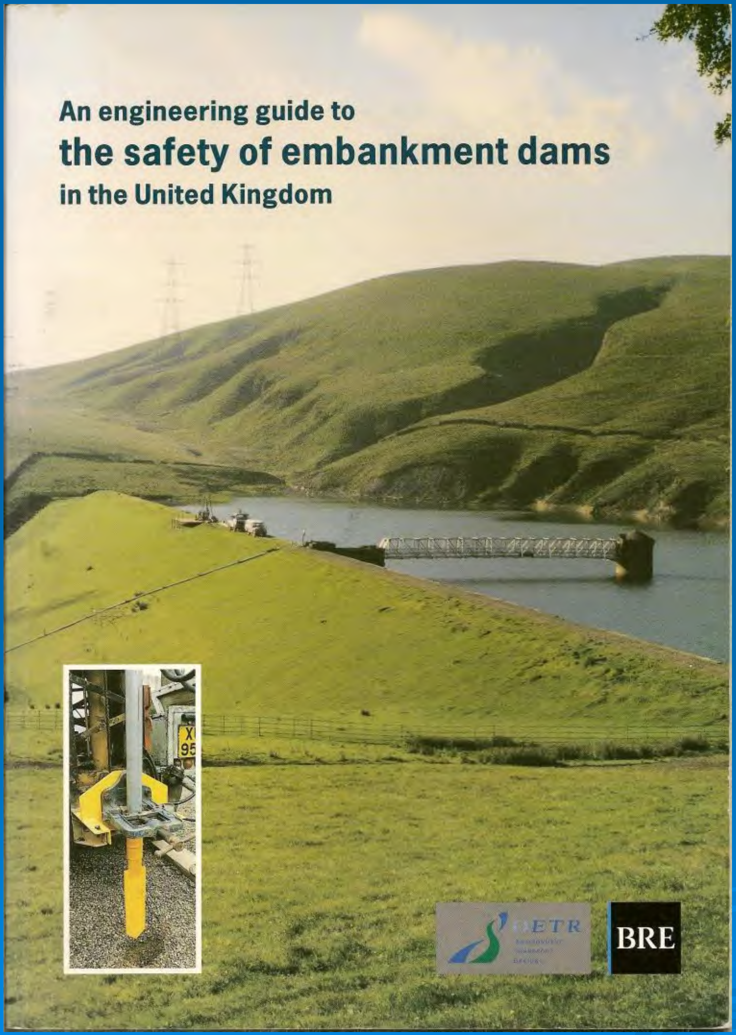
11: Other incidents

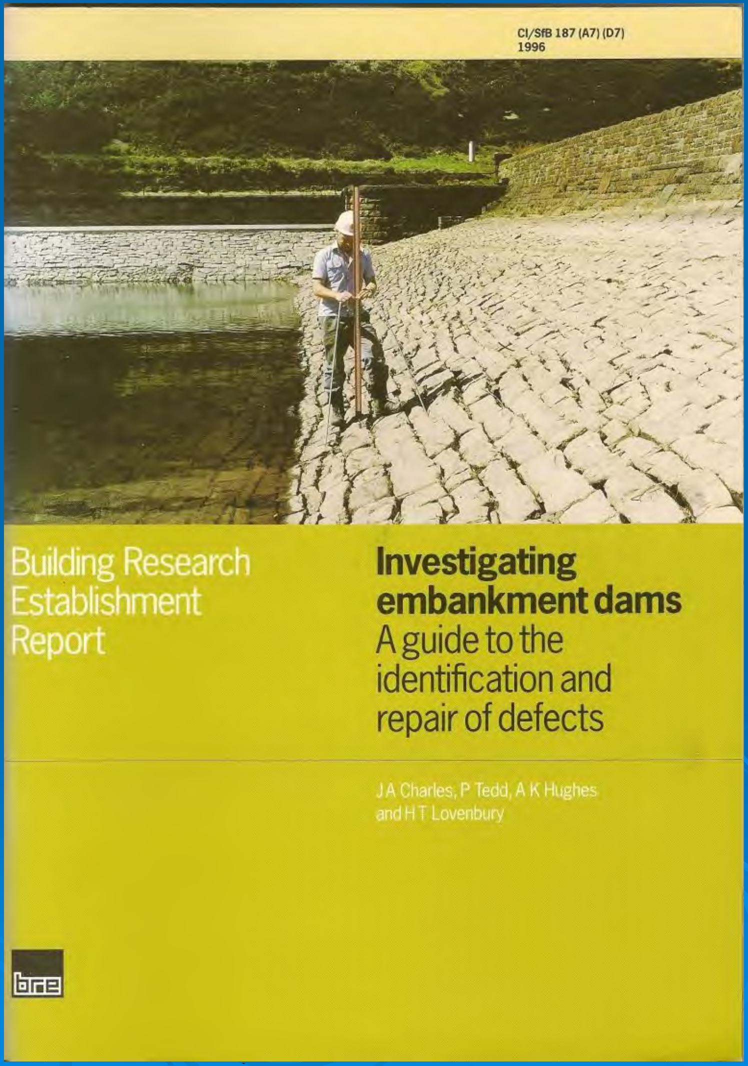
Other Dam Guides

- An engineering guide to the safety of embankment dams in the United Kingdom 2nd ed. BRE Report 363, (1999).
- Investigating embankment dams: a guide to the identification and repair of defects. BRE Report 303, (1996)
- Engineering guide to the safety of concrete and masonry dam structures in the UK. CIRIA Report 148 (1996).
- Small embankment dams. CIRIA Report 161 (1996).
- Valves, pipework and associated equipment in dams – guide to condition assessment. CIRIA Report 170 (1997).
- Dam and Reservoir Conduits CIRIA C743 (2015)

- Bibliography of British Dams on the BDS website contains over 1000 references

BRE Geotechnical Guides





Dolgarrog Failure – 2 November 1925

Two dams were involved:

Eigiau: 1 km long concrete gravity dam, 10m high. Built 1907 to 1911, vol. 4500 10^3 m^3.

Coedty: Earth dam with 0.6m wide concrete core, completed in 1924, vol 329 10^3 m^3

Built for the North Wales Power company for smelting aluminium. Dolgarrog failure led to the passing of the Reservoirs (Safety Provisions) Act 1930.

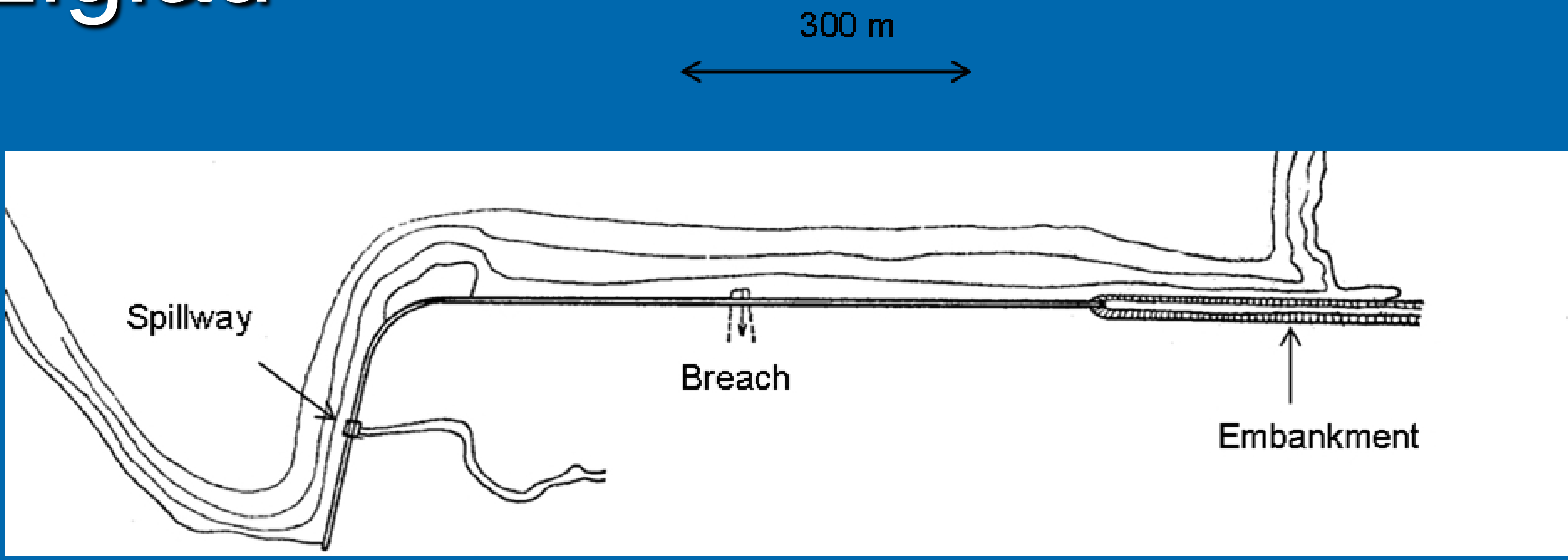
Dolgarrog 1925

Eigiau dam

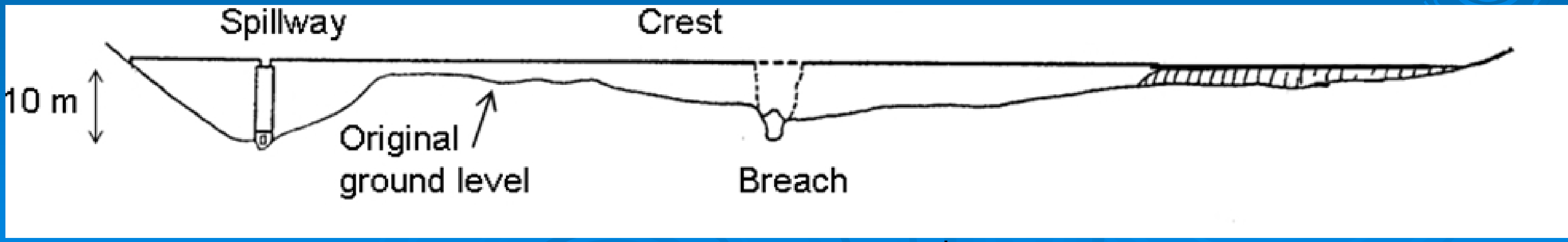
- Concrete gravity
- Completed 1911
- Height 5m at breach
- Shallow foundation on clay
- Poor concrete
- Remote location
- 16 killed, power station destroyed

Difficult Access

Eigiau

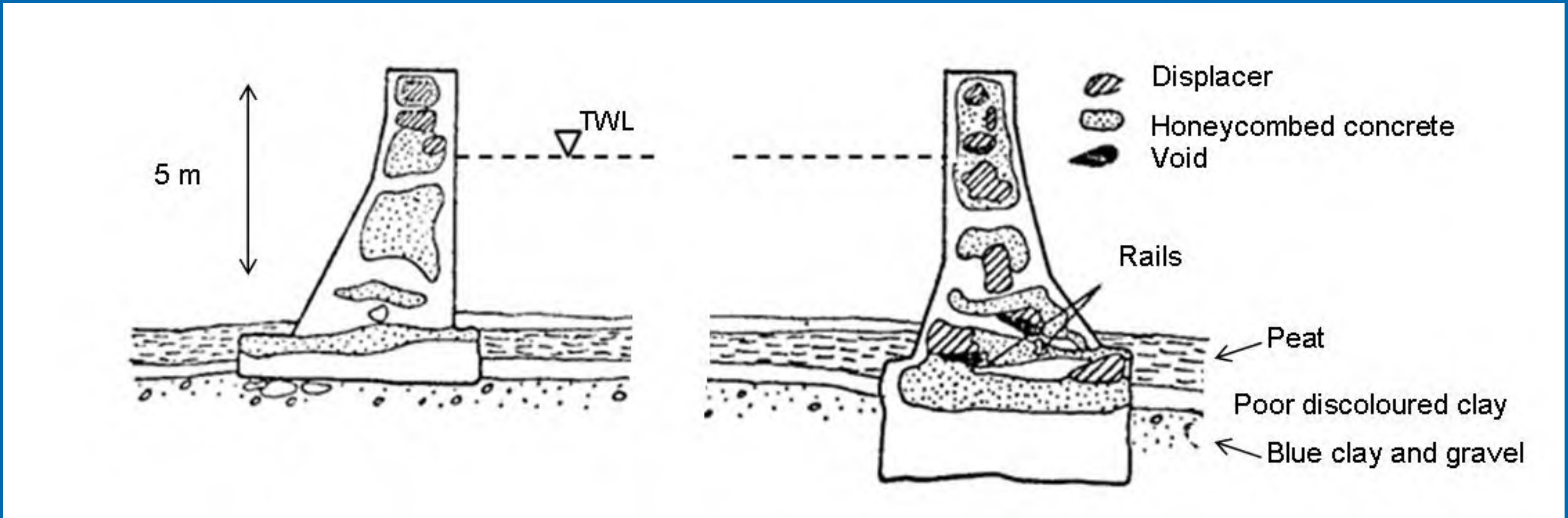


Plan



Longitudinal section

Eigiau

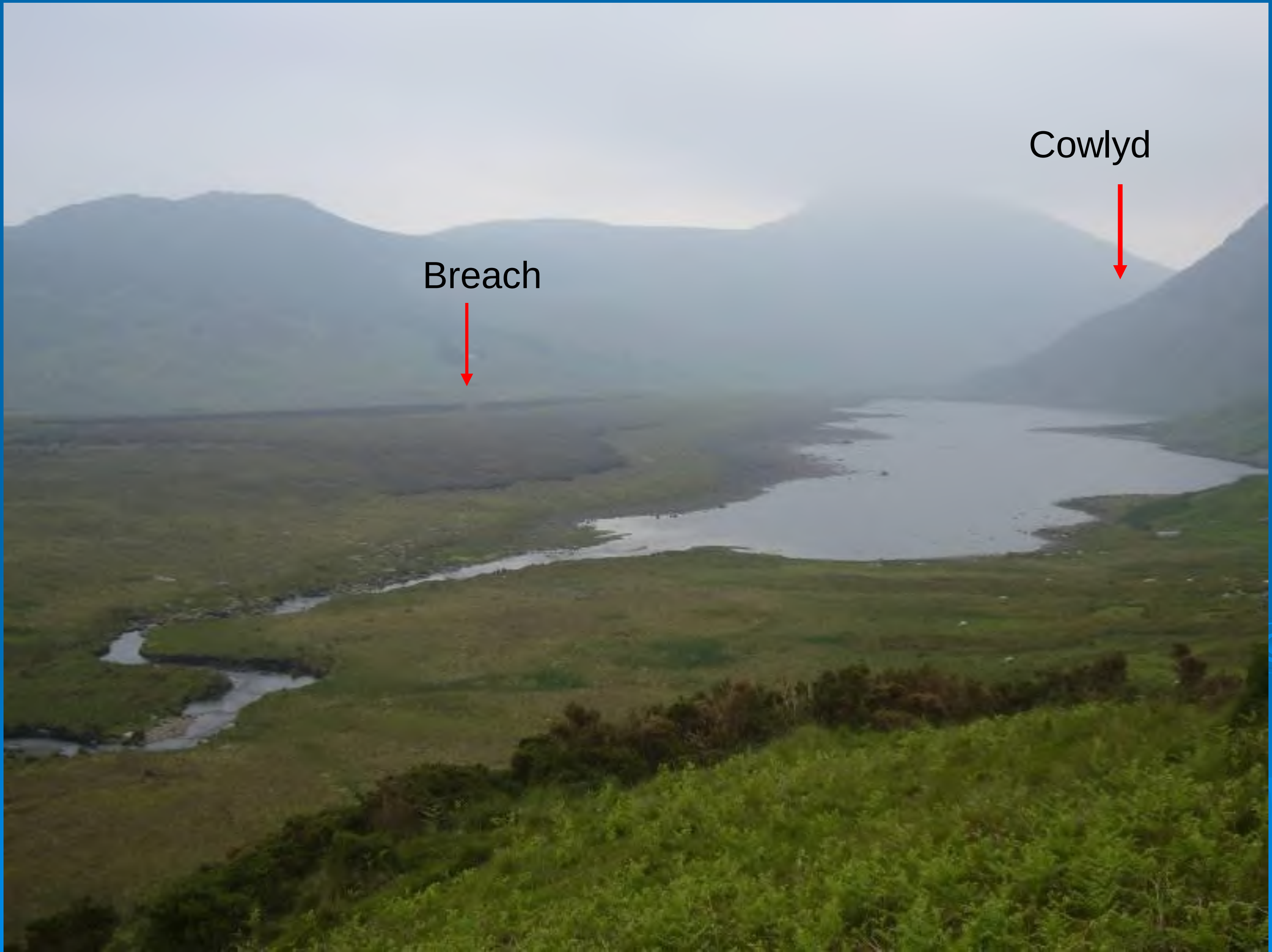


Foundation: glacial deposit of hard blue clay containing granite boulders, overlain by peat up to 1.5m.

Foundations were specified to be 1.8m below clay surface but were only 0.46m.

Eigiau breach 2009

Eigiau reservoir 2009



Cowlyd

Built 1921, 14m high,

Capacity 9430 10^3 m^3

Earthfill moraine fill dam, Concrete core

31 December 1924

Overtopped and nearly failed. Severe erosion of downstream fill to foundation level.

New Years Eve was spent repairing the dam.

Eigiau "concrete"

Coedty

Coedty

Lessons

- Technical evidence at the inquest was given by Ralph Freeman to the effect that the foundation of the Eigiau dam had not been sufficiently deep. The jury returned a verdict of accidental death: "*caused by the bursting of the dam under the wall in consequence of the wall lacking a proper foundation*" The coroner's jury recommended regular government inspection.

- Following the Skelmorlie and Dolgarrog disasters, a critical step towards reservoir safety legislation occurred when a letter to *The Times* from Edward Sandeman, a leading dam engineer, was published on Friday 4 December 1925.

BRS Geotechnics 1929 to 2013

- 1921- BRS was formed
- 1929 - Professor Jenkin from Oxford University starts work on soils
- 1933 - Soil physics section formed under Dr Cooling
- Skempton 1936 to 1947 Soil Mechanics Section
- 1962 Cooling gave 2nd Rankine Lecture
- 1997 Privatised
- 2013 - 80th anniversary of Geotechnics at BRE!

  last man retires

Soil Physics Section, – The Cow Shed, 1930 - 40s

Top of ladder - Golder

Cooling, ?, Skempton

Geotechnics Division 1970

Six Rankine Lectures

Annual lecture of the British Geotechnical Association (Society)

BRE Rankine Lectures

	At BRE	Lecture date
Cooling	1933 – 1968	(1962)
Skempton	**1936 – 1945**	**(1964)**
Bishop	**1944 – 1946**	**(1966)**
Gibson	1951 - 1956	(1974)
Ward	1942 – 1978	(1978)
Penman	**1944 – 1982**	**(1986)**
Burland	**1966 – 1980**	**(1990)**
Randolph	1973 – 1977	(2003)
Charles	**1966 – 2002**	**(2008)**

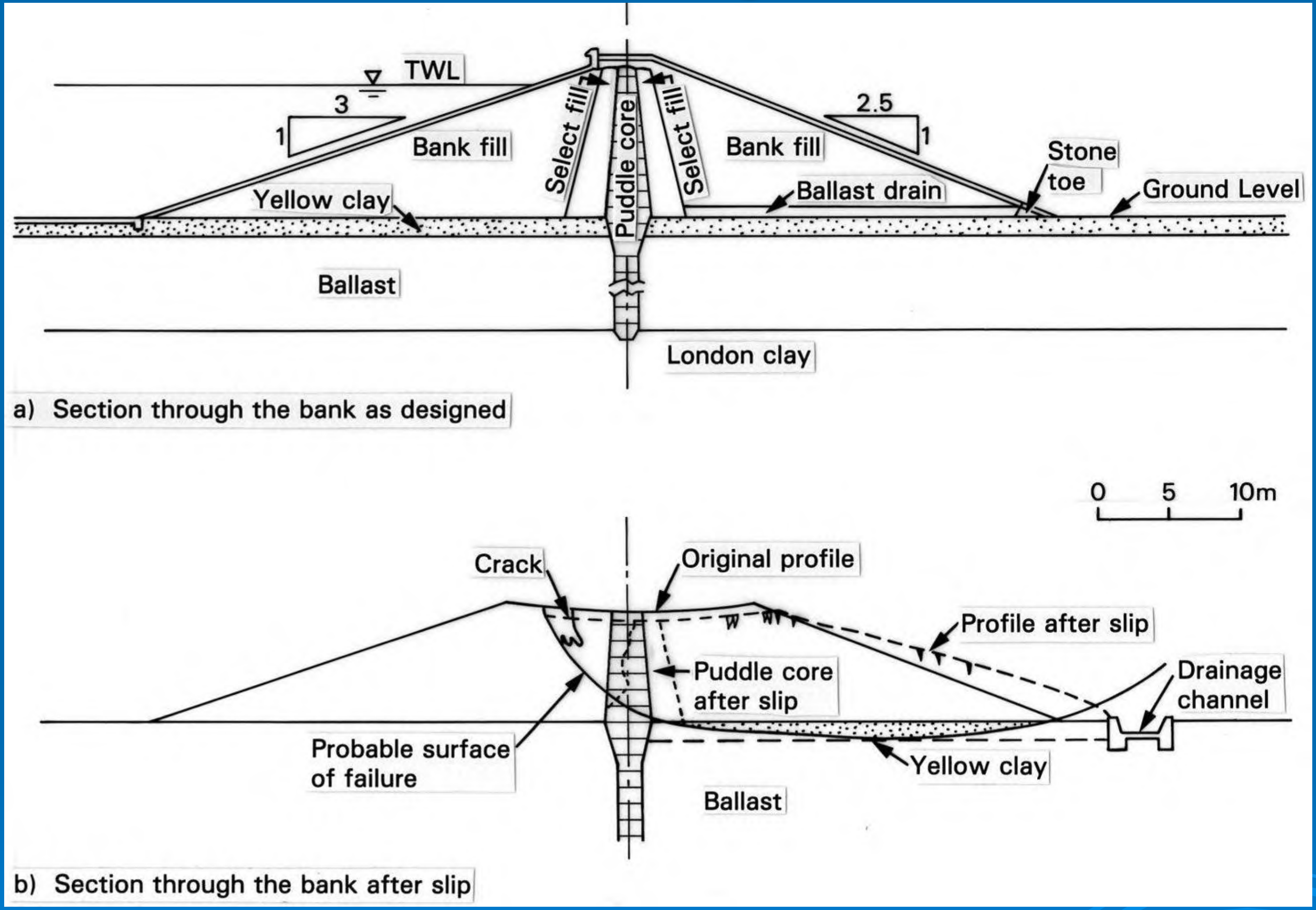
Also a Geoffrey Binnie Lecturer

BRS First Dam Investigation

William Girling (Chingford No 2)

- Bunded reservoir some 3.5 miles long 10m high built for Metropolitan Water Board adjacent to River Lea.
- 29 July 1937 - a 90m length of the downstream slope failed on a slip surface passing through the core and the layer of soft yellow alluvial clay.
- At this section, the embankment had been built to a height of 8 m in 11 weeks using modern earth-moving equipment imported from America.

Shear failure during construction



Skempton's first big investigation

Redesigned with the help of Terzarghi

Cooling & Golder, 1942

Chingford Slip

Factors influencing failure of Chingford

- Presence of soft weak clay in foundation, undrained shear strengths of 10 to 14 kPa
- Development of high pore water pressures due to rapid construction
- Little dissipation of pore water pressures
- King George V across the road had been built roughly at one third the rate had no problems.

Abberton Dam

Deep seated upstream slip during construction 20 July 1937, nine days before Chingford

French et al, 2000

BRE Dam Safety Research 1937 -1980s

- Slope stability during construction

  Chingford, Muirhead, Knockenden, Usk

- Investigations during construction and operation

  Carsington New, Llyn Brianne, Megget, Roadford, Scammoden, Winscar,

1983 onwards - safety of old puddle clay core dams

- Review of incidents and failures
- Field and Laboratory Investigations

1. Deformation studies
2. Internal erosion studies
    - Stresses in clay cores
    - Hydraulic fracture tests
    - Clay erosion tests
    - Filter properties of downstream fill

Typical section of puddle clay core dam

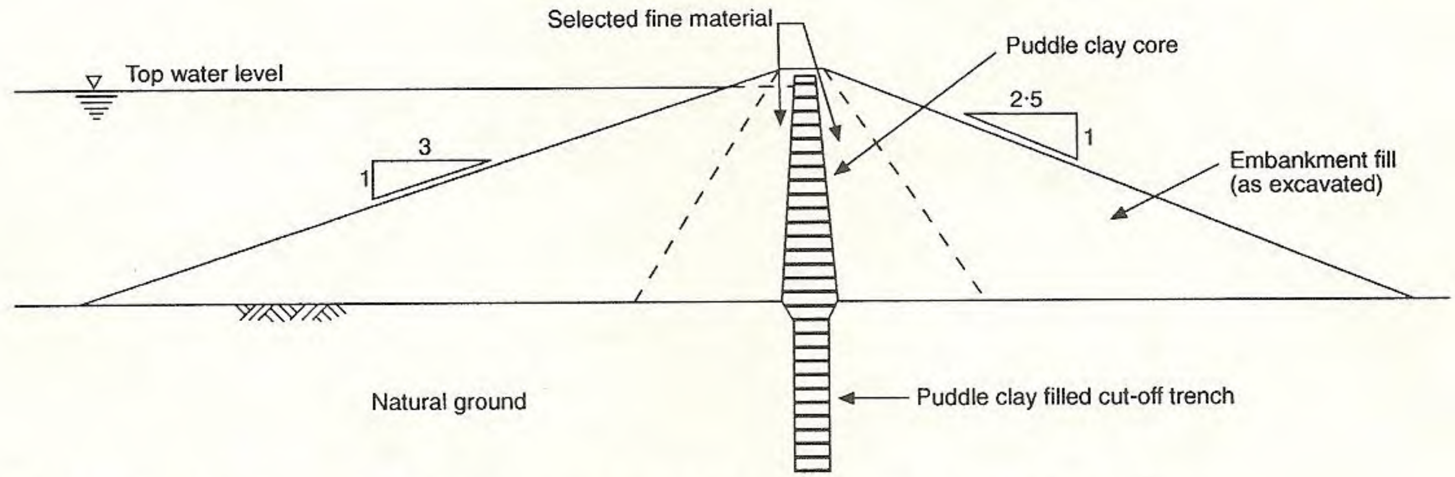


Fig. 1. Typical cross-section of an old embankment dam with a central puddle clay core

Embankment Deformation Studies
Main causes are:

- Primary consolidation of embankment and foundation
- Collapse compression of upstream fill
- Secondary consolidation
- Stress changes due to reservoir fluctuation
- Internal erosion
- Slope instability
- Volume change in clay due to seasonal change in moisture content

Deformation Studies from 1987 to 2002

- Ramsden: Puddle clay core, concrete cut-off
- Walshaw Dean Lower: Puddle clay core, and deep narrow cut-off
- Yateholme: Puddle clay core,
- Ogden: Puddle core and upstream clay blanket
- Holmestyes: Puddle core and upstream clay blanket

Ramsden Dam

Location: Holmfirth

Built: 1879 -83
Engineer: G H Hill of Bateman and Hill
Height: 25 m
Settlement: 1m (4% vertical settlement) since construction

Measurements by Yorkshire Water showed that settlements were related to reservoir drawdown. Concerns were expressed about slope instability and internal erosion

Instrumentation

- Precise surveying to monitor surface vertical and horizontal movements
- Subsurface Movements

    Vertical - magnet settlement gauges

    Horizontal - Inclinometers
- Piezometers – standpipe and pneumatic
- Push-in pressure cells

Magnet Settlement Gauge

- Invented in the late 1960’s. BRE and Soil Instruments
- Installed in borehole or built up during construction
- Basic components
  - Magnets fixed to the sides of borehole (springs and grout) and move with the embankment
  - Reed switch that is lowered down access tube on a measuring tape that closes in magnet’s field, completing a circuit
- Can install any number of magnets, 2 -3 m in puddle clay core dam
- Accuracy – better than 1mm with micrometer system
- Length of gauge can be increased or decreased
- Longevity – 15 years plus

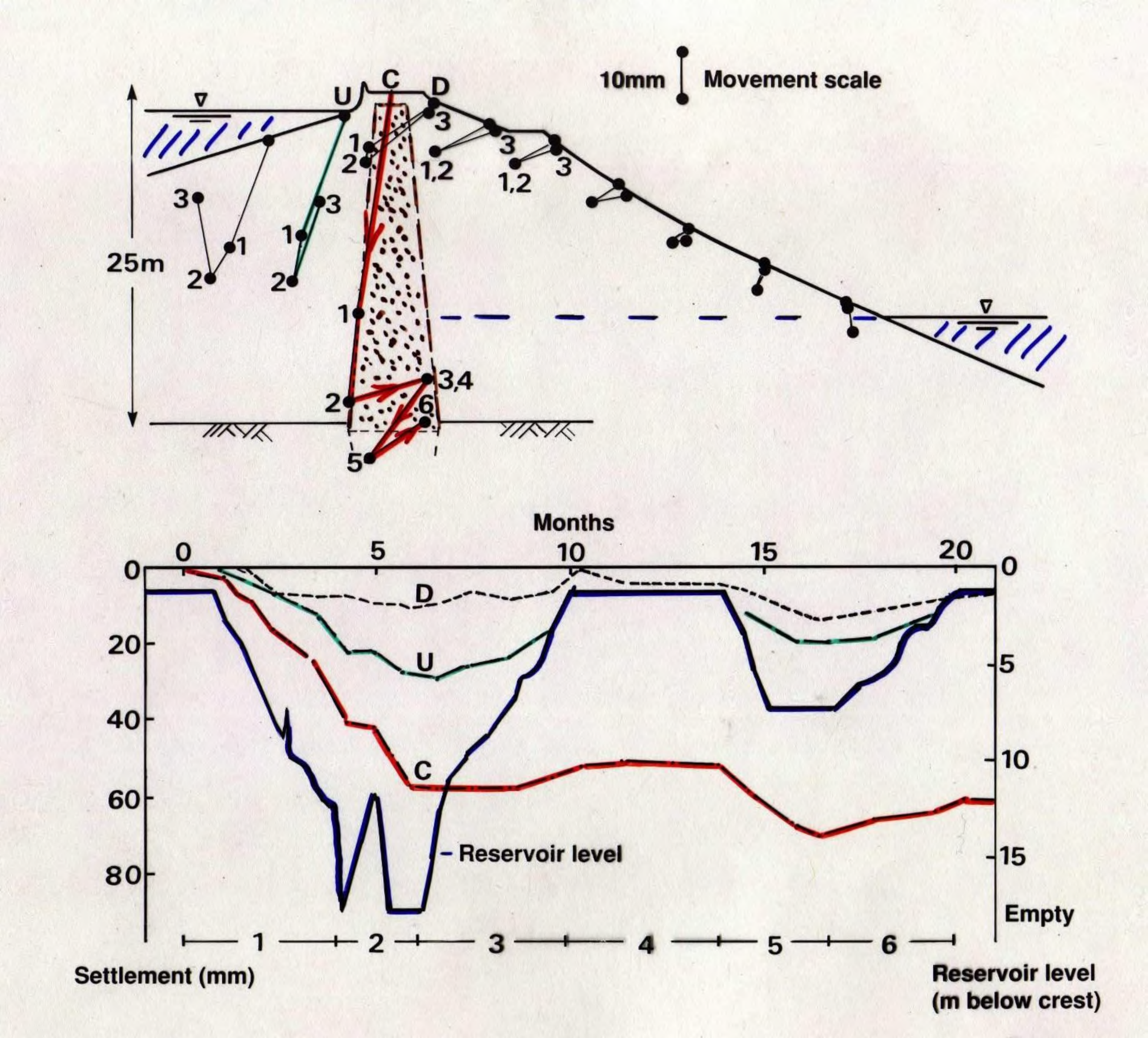
Drilling

Magnet settlement gauge

Importance of zero readings

Zero readings without getting wet

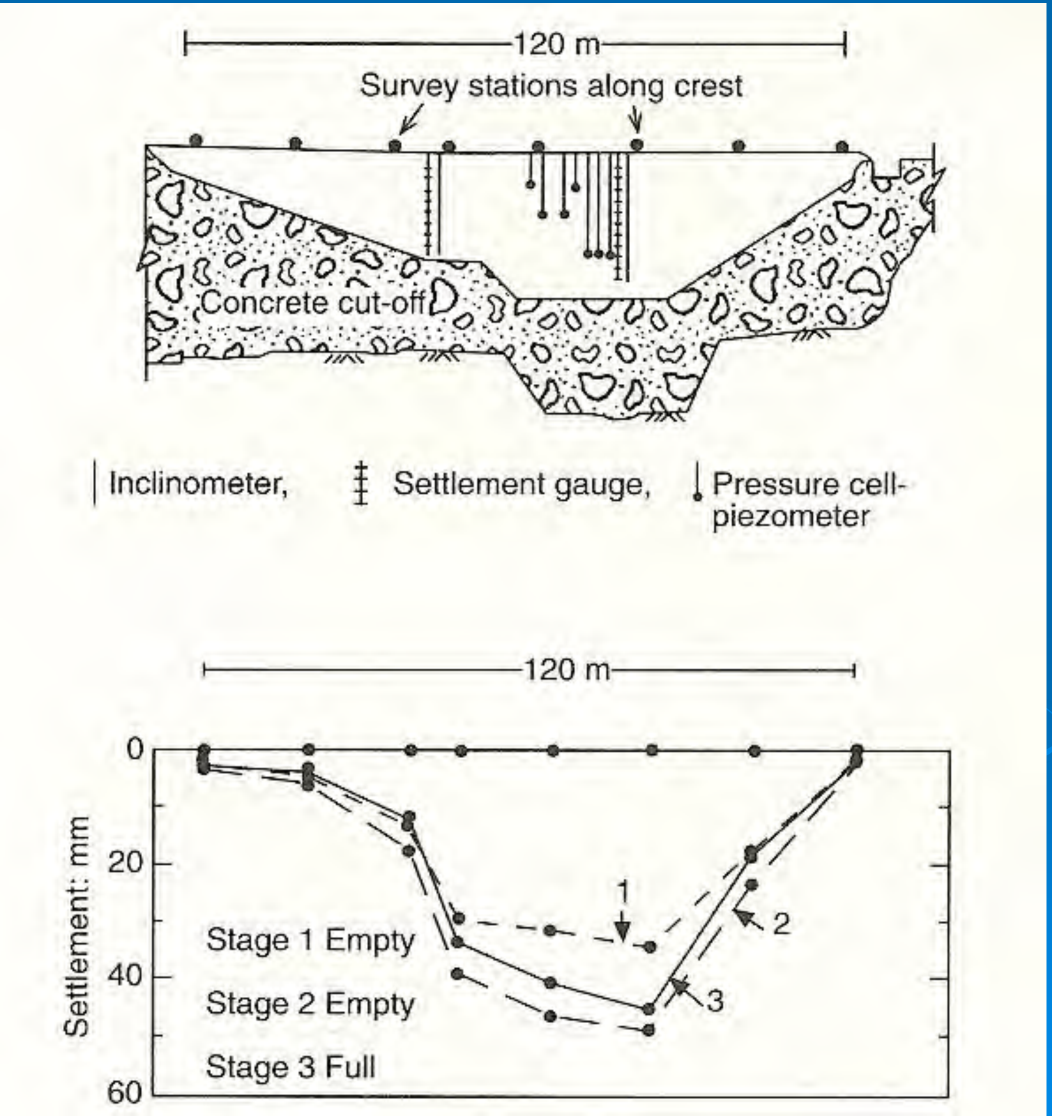
Ramsden – surface movements due to reservoir changes



Settlement along crest

Settlement related to:

- ➢Depth of fill
- ➢Duration of drawdown
- ➢Depth of drawdown
- ➢History of drawdown



Settlement and horizontal movement with depth

Stage 1: Empty

Stage 2: Empty

Stage 3: Full

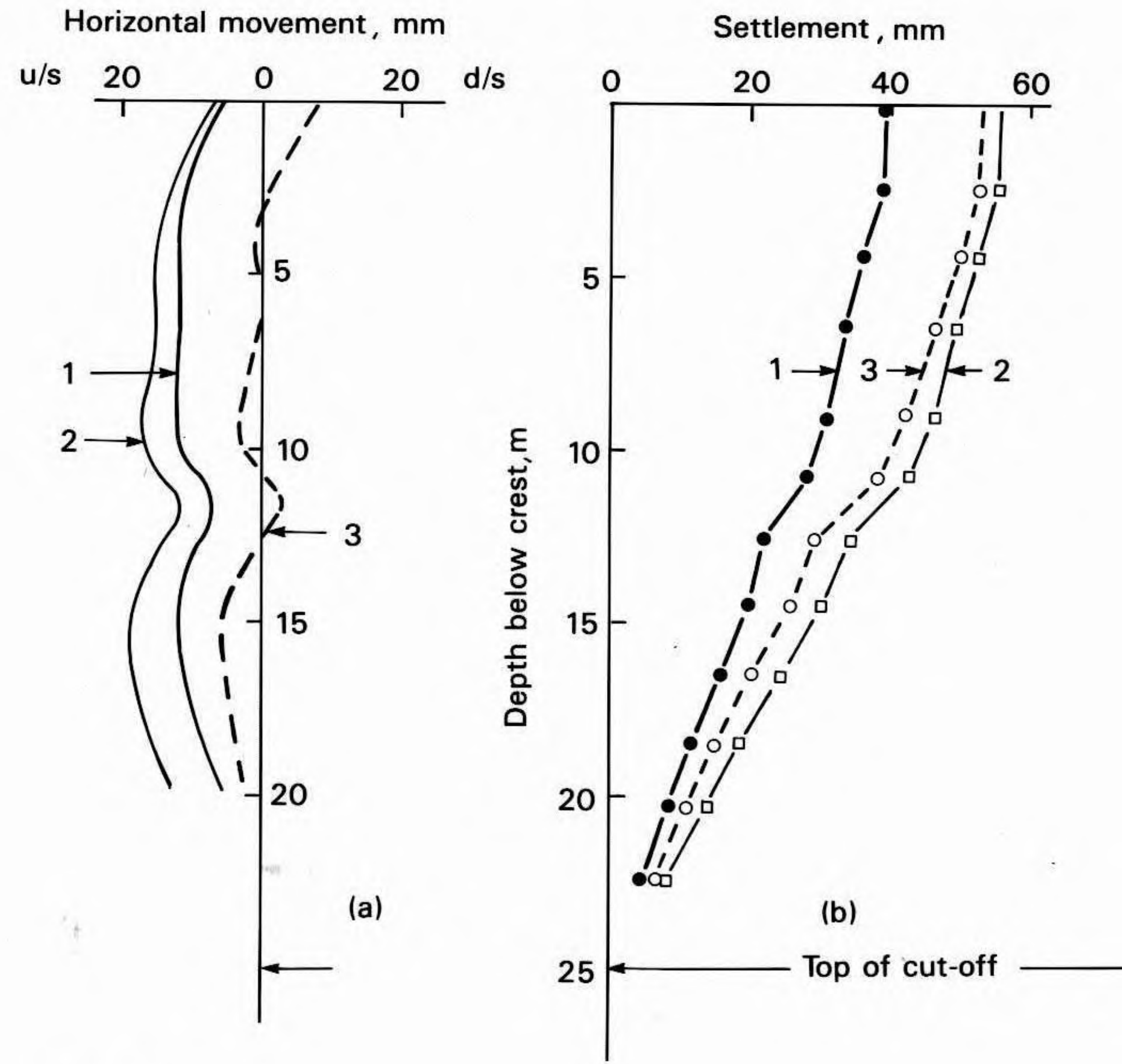


Figure 4

Crest settlement and recovery due to reservoir drawdown and refilling

	Empty	6m
Maximum settlement on drawdown	58mm	16mm
Settlement recovered on refilling	16mm	8mm
Percentage recovered on refilling	10	50

Summary of surface measurements

Reservoir drawdown

- Settlement of the crest and upstream slope
- Upstream horizontal movement of the crest, and upstream and downstream slopes close to the crest

Reservoir refilling

- Some heave of the crest and upstream slope, but significantly less than the settlement caused by reservoir drawdown
- Downstream horizontal movement of the crest larger than the upstream movement

Mechanisms causing deformation due to reservoir fluctuations

Upstream fill

- Drawdown causes increase in effective stress

Puddle clay core

- Drawdown reduces total lateral pressure acting on the upstream side of the core
- Change in drainage conditions allows consolidation of the core

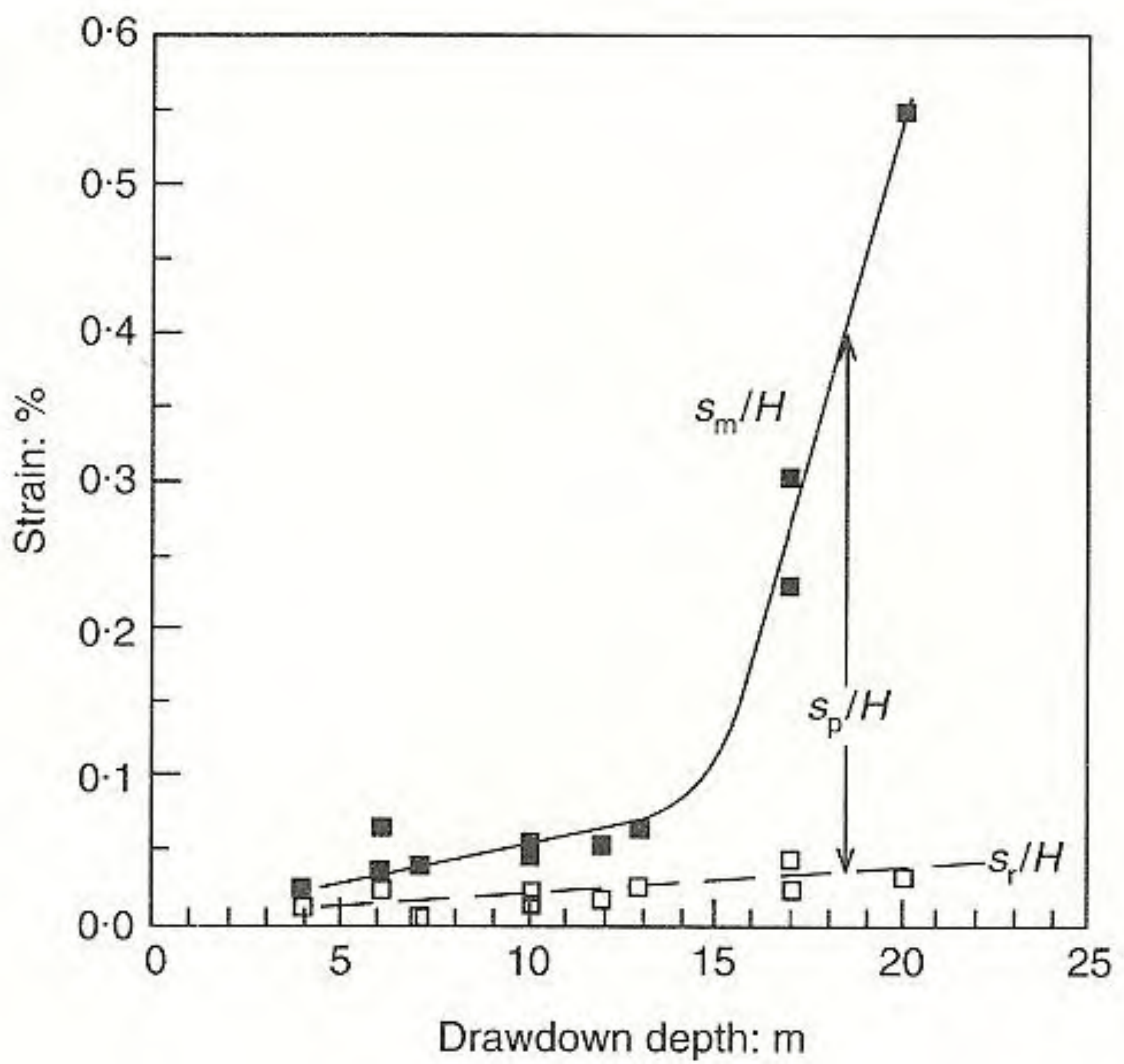
Crest settlement data expressed as vertical strain against reservoir drawdown

Sm/H, maximum strain

Sp/H, permanent strain

Sr/H, recovered strain on refilling

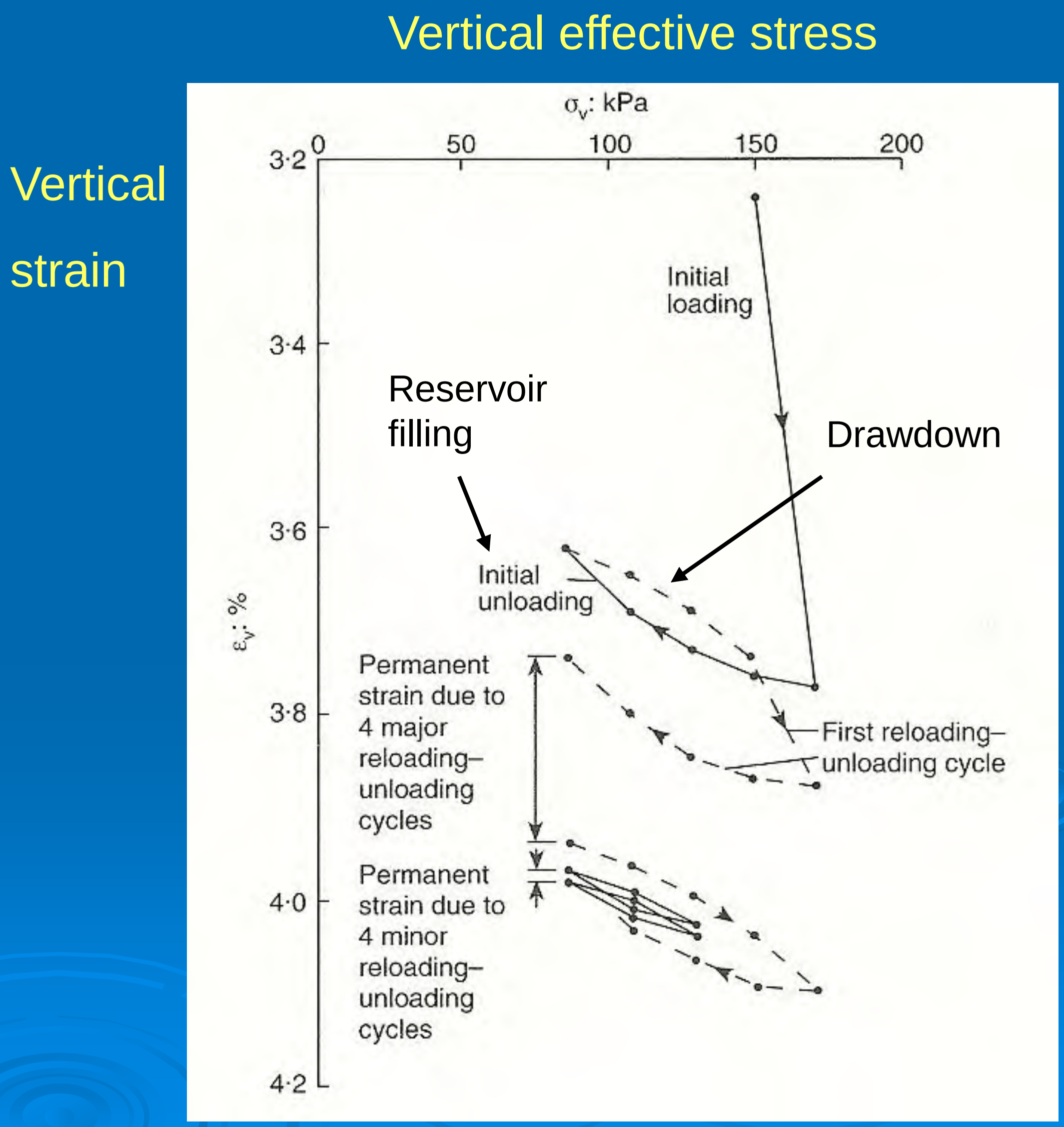
Crest Settlement, mm	
Ramsden	58
Walshaw Dean	14
Ogden	138
Brownhill	176
Digley	58
Holmestyes	-1



Oedometers Tests on Upstream Fill

Stress-strain behaviour is not linear. Constrained modulus values decrease with increasing reloading (reservoir drawdown) 113 MPa to 31 MPa.

Each load cycle resulted in non-recovered strain. The non-recovered strain for the major reloading-unloading cycle was 13 times that for the minor cycle.



Significance of measurements and analyses

- Large and non-recoverable movements can occur during operational cycles of drawdown and re-impounding of old puddle clay core dams with free draining shoulders, even though the factor of safety against an overall shear failure is quite high.
- They do not indicate that there is not an adverse situation developing after many years of operation, except for loss of freeboard.

- They have been used to predict the long term settlement at other dams, eg Ladybower.

Holme Styes

- Built 1840, design by George Leather for the Holme Reservoirs Commissioners
- 24m high with puddle clay core and shallow cut-off.
- Valve shaft immediately upstream of the core
- Captain Moody, government inspector for the failure of Bilberry dam, reported that "leakage into the valve pit was running considerably muddy"
- Bateman placed an upstream clay blanket on the dam and adjacent sides in 1857

References: The Leeds Mercury 28 February 1852 Bilberry

Tedd, Robershaw and Holton (1993) Dams & Reservoirs

Dyke and Williams (1998) BDS Conference

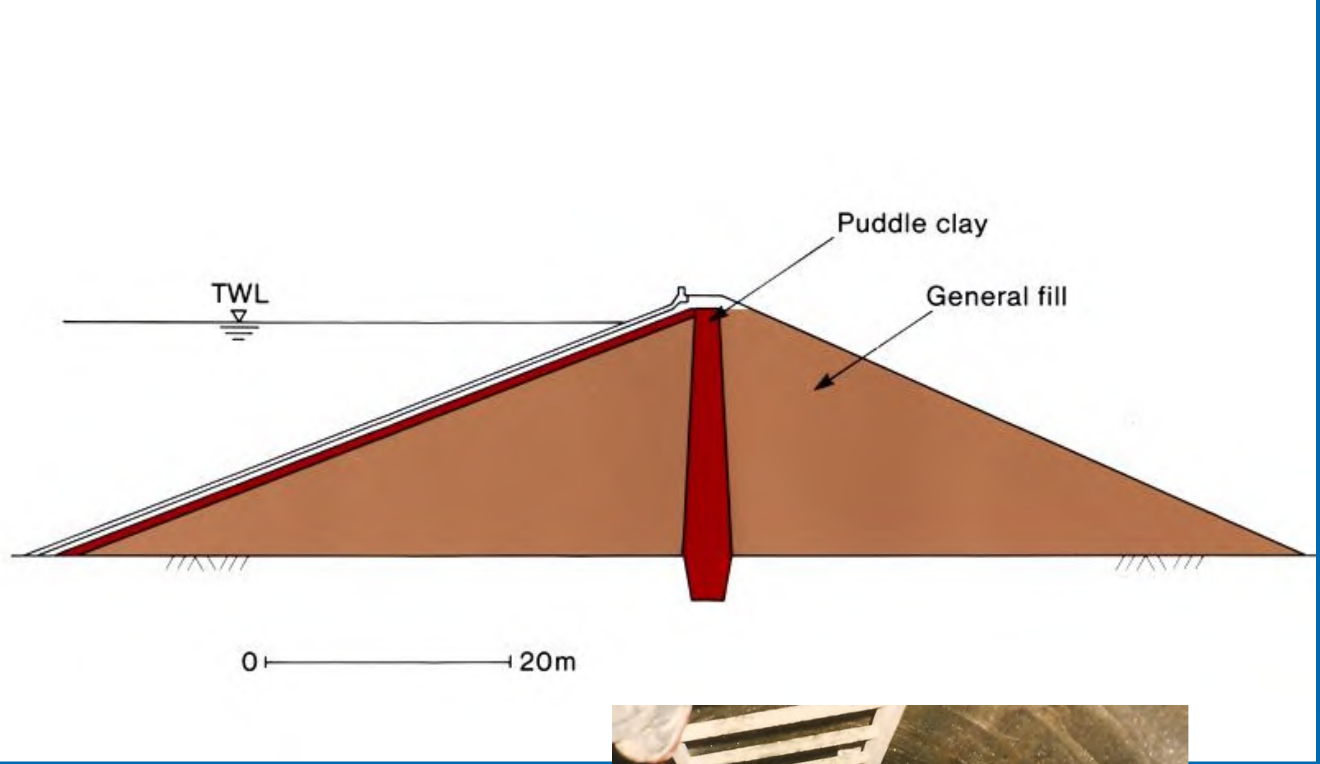
Inquest into failure of Bilberry, 1852

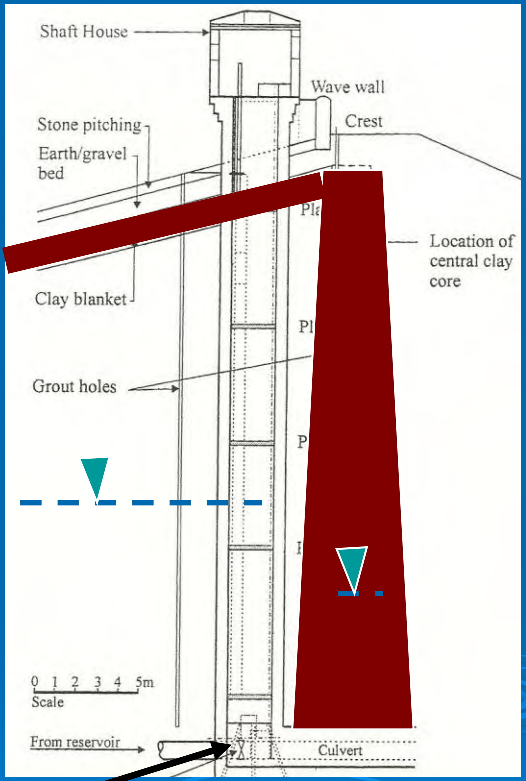
Captain Moody's comments on Holmestyes Reservoir

"From what I saw of it, you should not delay in sending for some superior engineer accustomed to this kind of work; take his advice, and carry what he advises into execution."

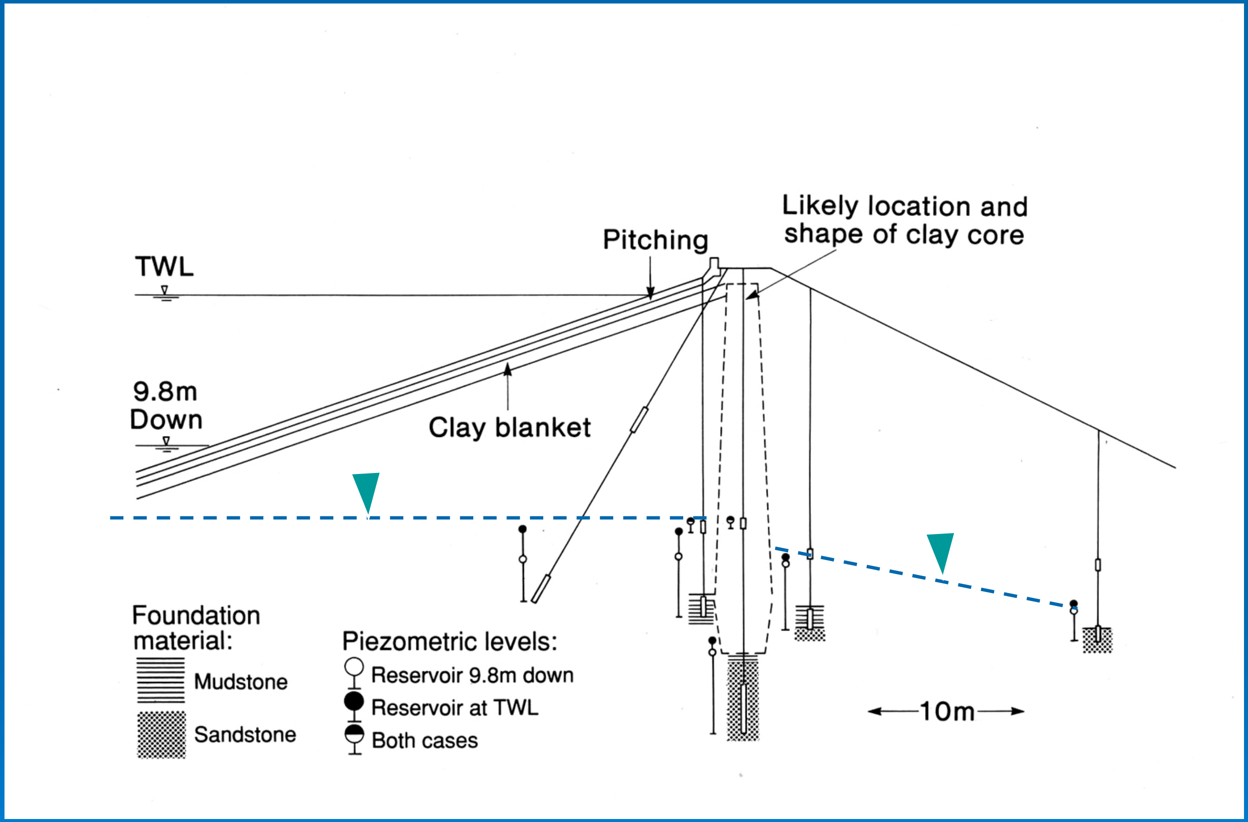
.. when I saw the reservoir, my expression was 'the people here must be insane' referring to the bye-wash with a wall across it

Concern: the build up of pore pressures in the upstream fill could lift the upstream clay blanket during reservoir drawdown.





Borehole investigations 1982, 89 and 91 included sampling, permeability measurements and piezometer installation



Boyles Rotary water flush rig enable angled drilling

Problems:

- Core recovery with plastic coreline
- Lack of back flush in upstream fill
- Difficulty of grouting upstream boreholes

Findings

- The piezometric measurements confirmed that the upstream blanket was generally effective.
- The upstream fill was very permeable with values in excess of 1×10^{-4} m/s
- The core was more permeable than at other dams, typically 5×10^{-7} m/s
- The dam crest wall heaved with reservoir drawdown

Settlement depends on position of watertight element

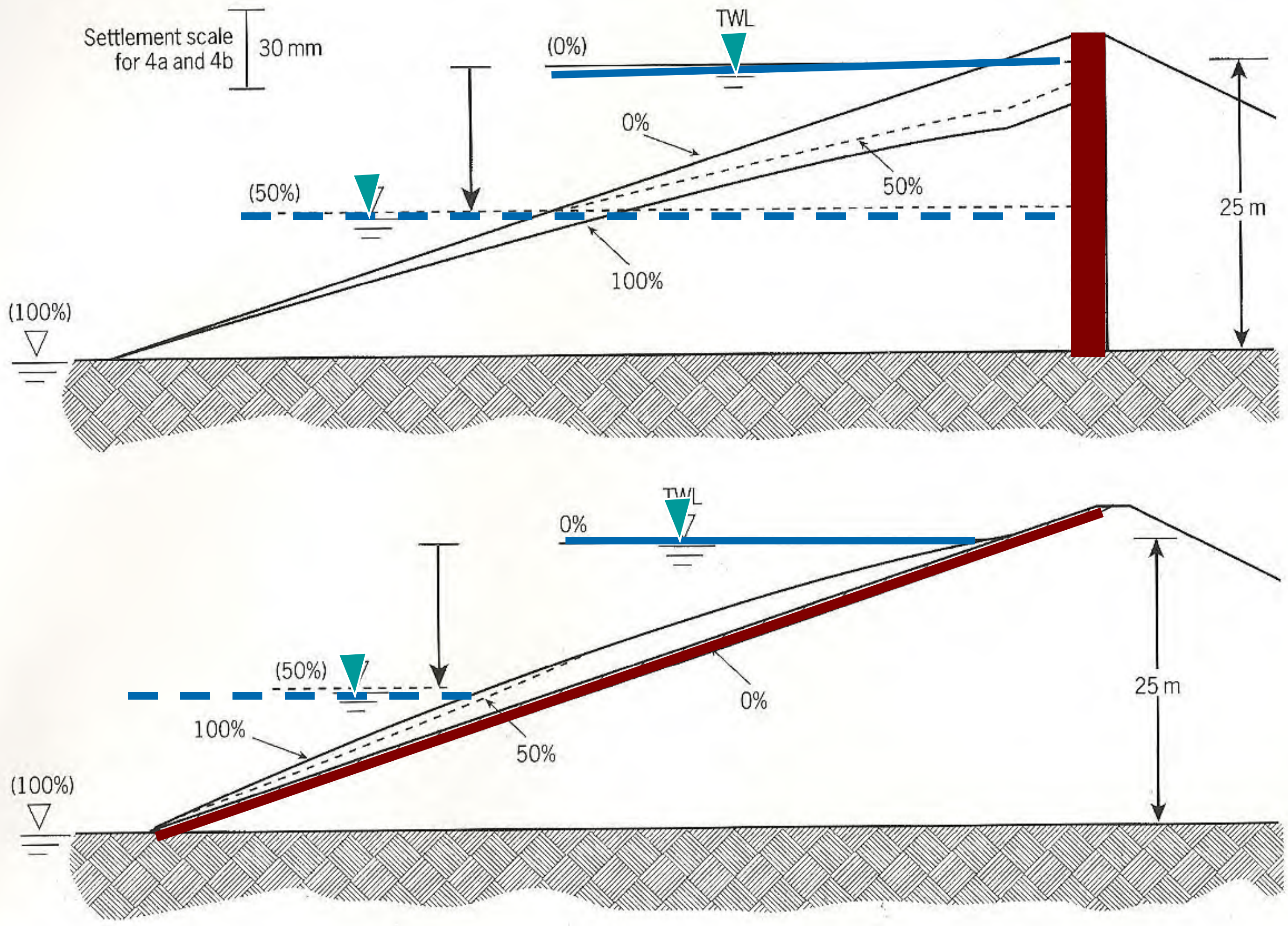


Figure 4 Settlement due to reservoir drawdown (after Charles *et al*, 1996)

Factors affecting Drawdown Settlements

- Position of watertight element
- Age of dam
- Construction materials, initial compaction, upstream fill permeability
- Number of drawdowns
- Depth of fill
- Depth of drawdown
- Length of drawdown
- Time since last major drawdown

Potential Mechanisms of Failure

- External erosion – overtopping, wind, waves
- Slope instability – drawdown, leakage, rainfall, inadequate drainage
- Internal erosion –
- through core or cut-off,
- into or along side draw-off or other interface eg. abutment
- from pressurised pipe, (conduit) through fill

Symptoms of Internal Erosion

- Damp areas, reeds
- Leakage, turbid leakage
- Embankment settlement, sinkholes
- Whirlpool in reservoir

Wet patches

Infra-red thermography study 1984 at Gorpley dam

Showed the wet areas (blue) to be cold compared with surrounding ground (green)

The Teton dam, June 1976

- Failed on first filling
- Cause - internal erosion
- Deaths 14

Huai Takien, Thailand

10m high, built with dispersive clay

Failure on first filling 1983 over period of 8 hours.

Knight 1985

Walshaw Dean Middle - first filling

Oakdale Lower

Nov 1986 sinkhole appeared without warning

Built 1890

Height 10m

Puddle core

Internal Erosion through Core

- Leakage through the core
- The crack once formed stays open
- The clay is erodible due to the passage of water
- If erosion does occur, it will not be halted by the filter properties of the downstream fill

Leakage Mechanism - hydraulic fracture

- Hydraulic fracture can occur when the pressure exerted by the reservoir water on any plane in the core exceeds the total earth pressure acting on that plane.
- It is suggested that two conditions are necessary for hydraulic fracture: 1) stress conditions 2) an initiating zone such as an existing crack or more permeable layer.
- The susceptibility of a clay core dam to hydraulic fracture is related to stress reduction associated with differential settlement of the core relative to stiffer adjacent fill, foundations, abutments, structures, conduits

Measurement of Total Stresses

- Self-boring-pressuremeter
- Dilatometer
- Stepped blade
- Critical pressure tests

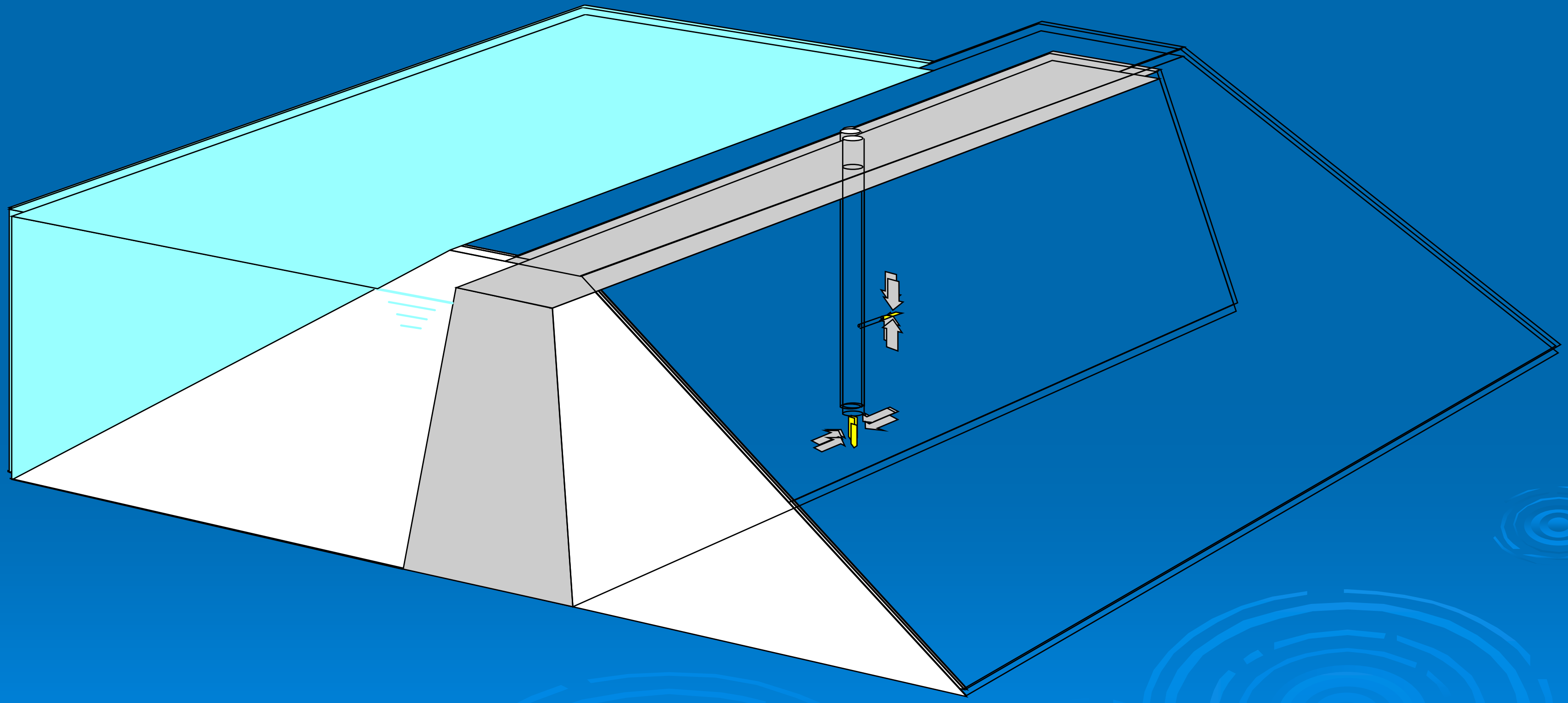
Permanently installed instruments

- Push-in spade cell (only measure horizontal stress)
- Miniature earth pressure cell (vertical and horizontal stress)

Dams studied

- Cwm Wern Deri
- Challacombe
- Gorpley
- Ramsden
- Walshaw Dean Lower and Upper
- Woodhead
- Staines South
- King George VI
- Wrasbury
- Queen Mother

Push-in Pressure cells



Push-in pressure cells

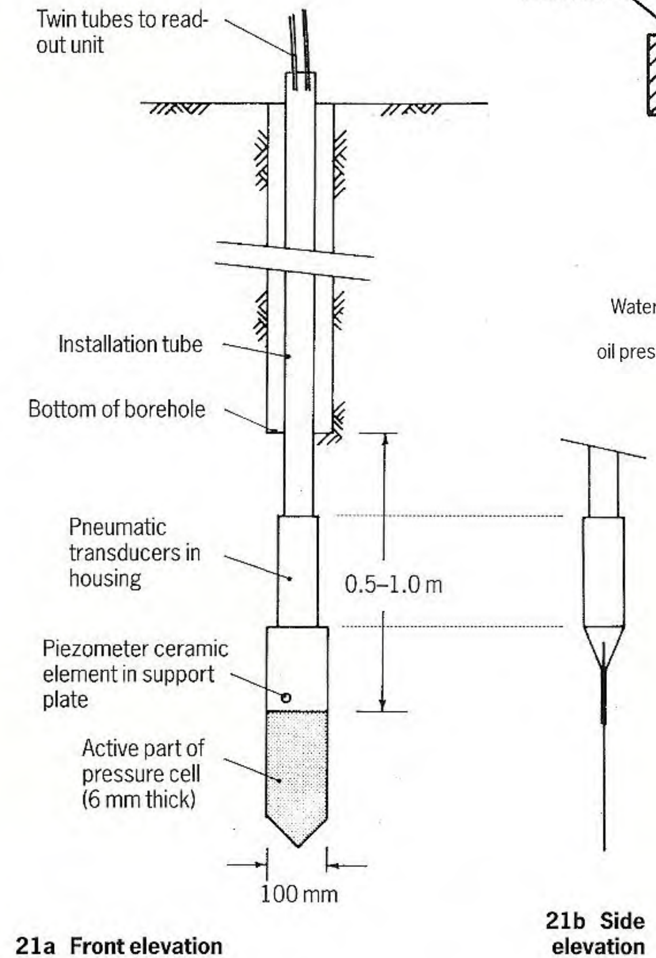
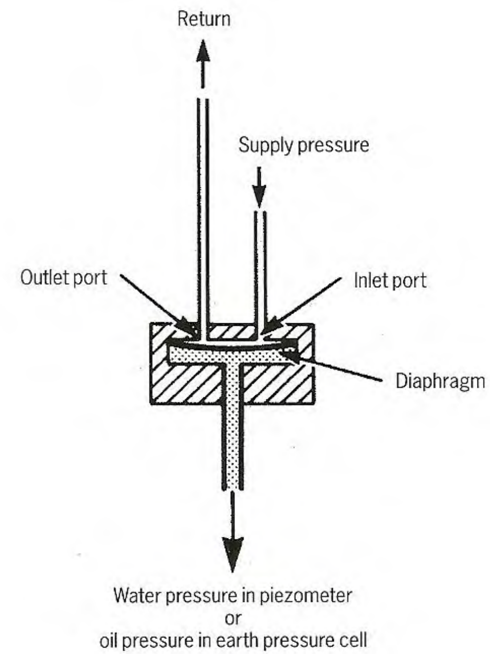


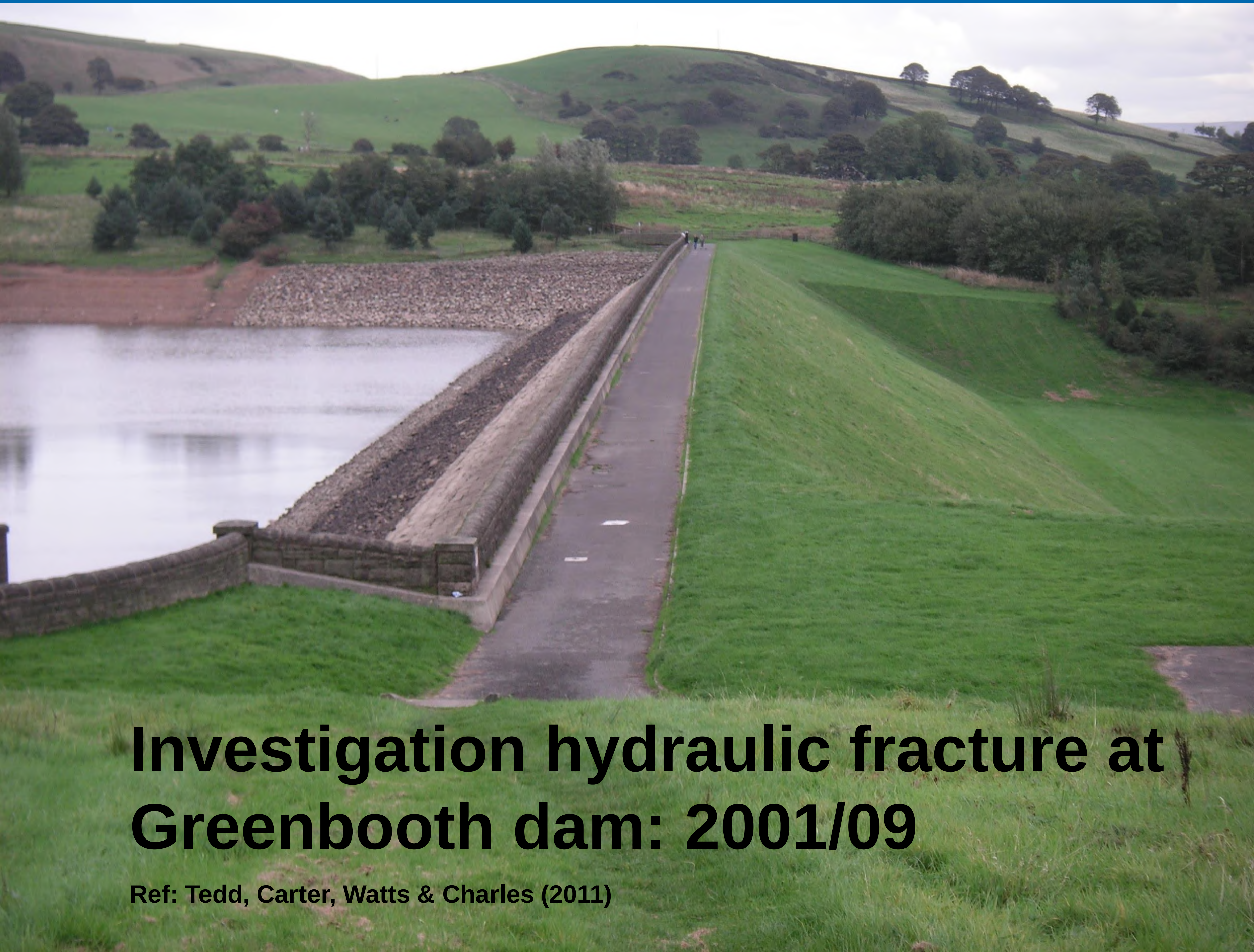
Figure 21 A push-in earth pressure cell



Miniature earth pressure cells

- Max 6 per borehole
- Measures horizontal and vertical stress
- Only suitable for soft clay
- Good longevity

Estimating over read using a borrowed IOWA stepped blade



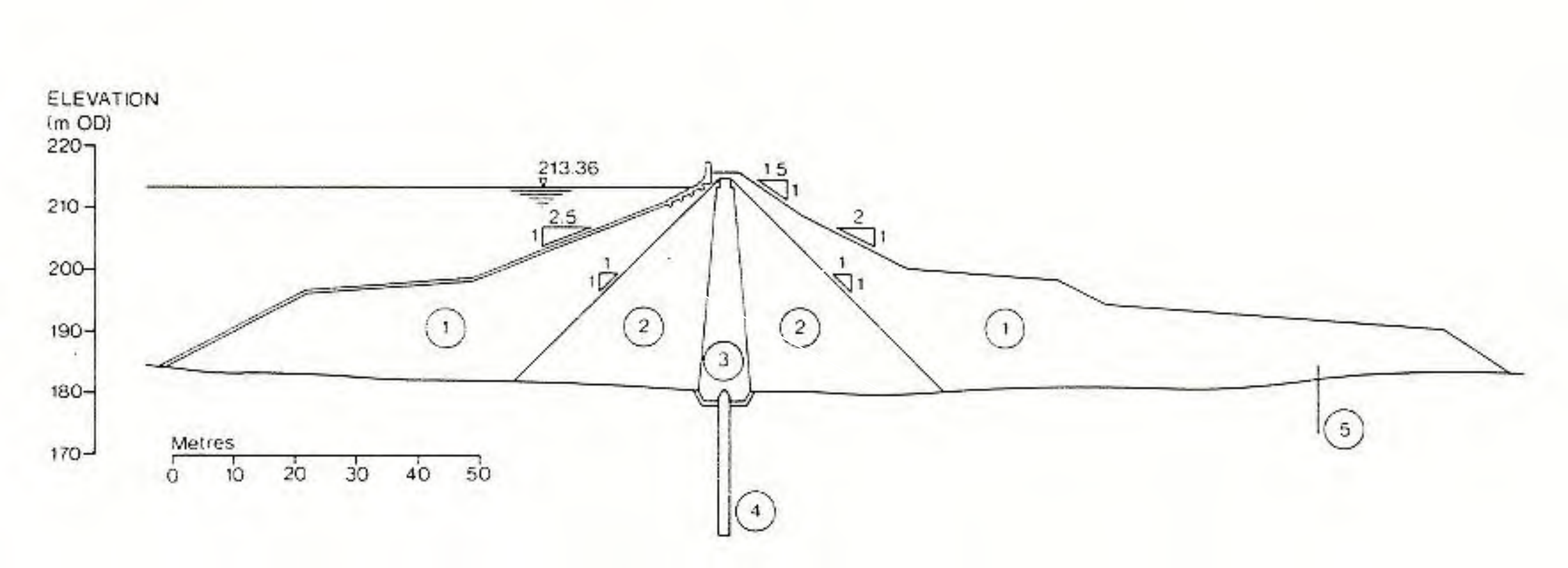
Investigation hydraulic fracture at Greenbooth dam: 2001/09

Ref: Tedd, Carter, Watts & Charles (2011)

Construction Summary

- Location - Rochdale
- Engineer – G H Hill
- Constructed – 1958-61
- Height – 35m
- Heavy earthmoving and compaction equipment
- Puddle clay core dam with concrete cut-off
- Core width - 8.2m at base, 2.7m at crest
- Tarmac crest

Greenbooth: Cross-section



1 - Sandstone fill

2 - Shale fill

3 – Puddle clay

4 – Concrete

5 – Sheet pile

Incidents, investigations, repairs

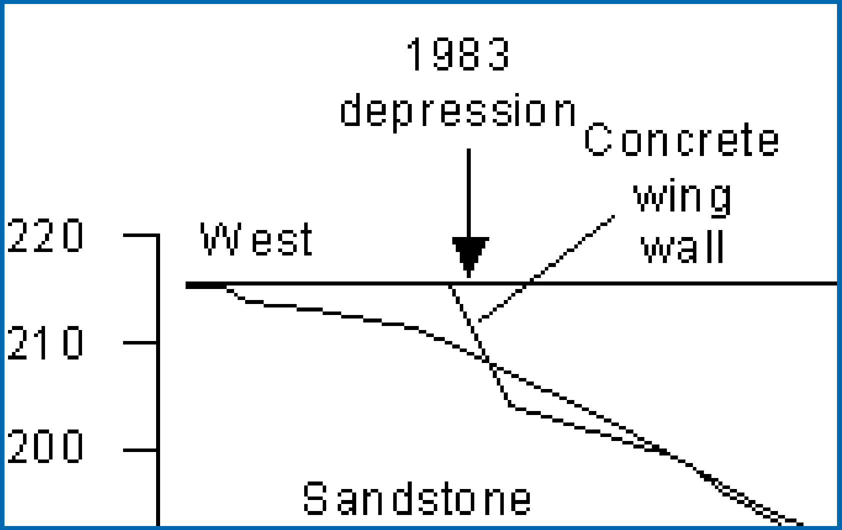
- 1961 – Construction instability (high pore pressures and toe movement) resulting in re-design with additional berms and sheet piling.

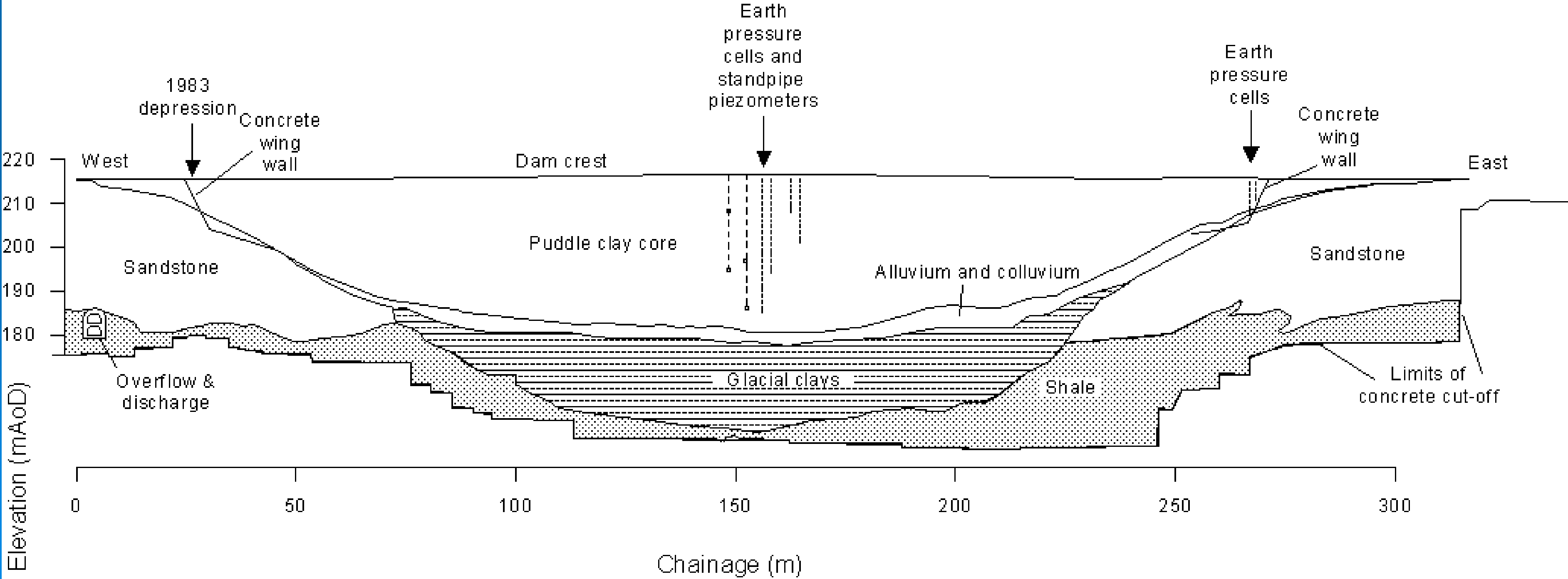
- 1975 – Crest had settled adjacent to abutments.

- 1983 – A shallow depression had formed on the crest above the toe of the west wing wall (noticed by a dog walker). Remedial grouting involved 440 cubic metres, 4% of treated volume.

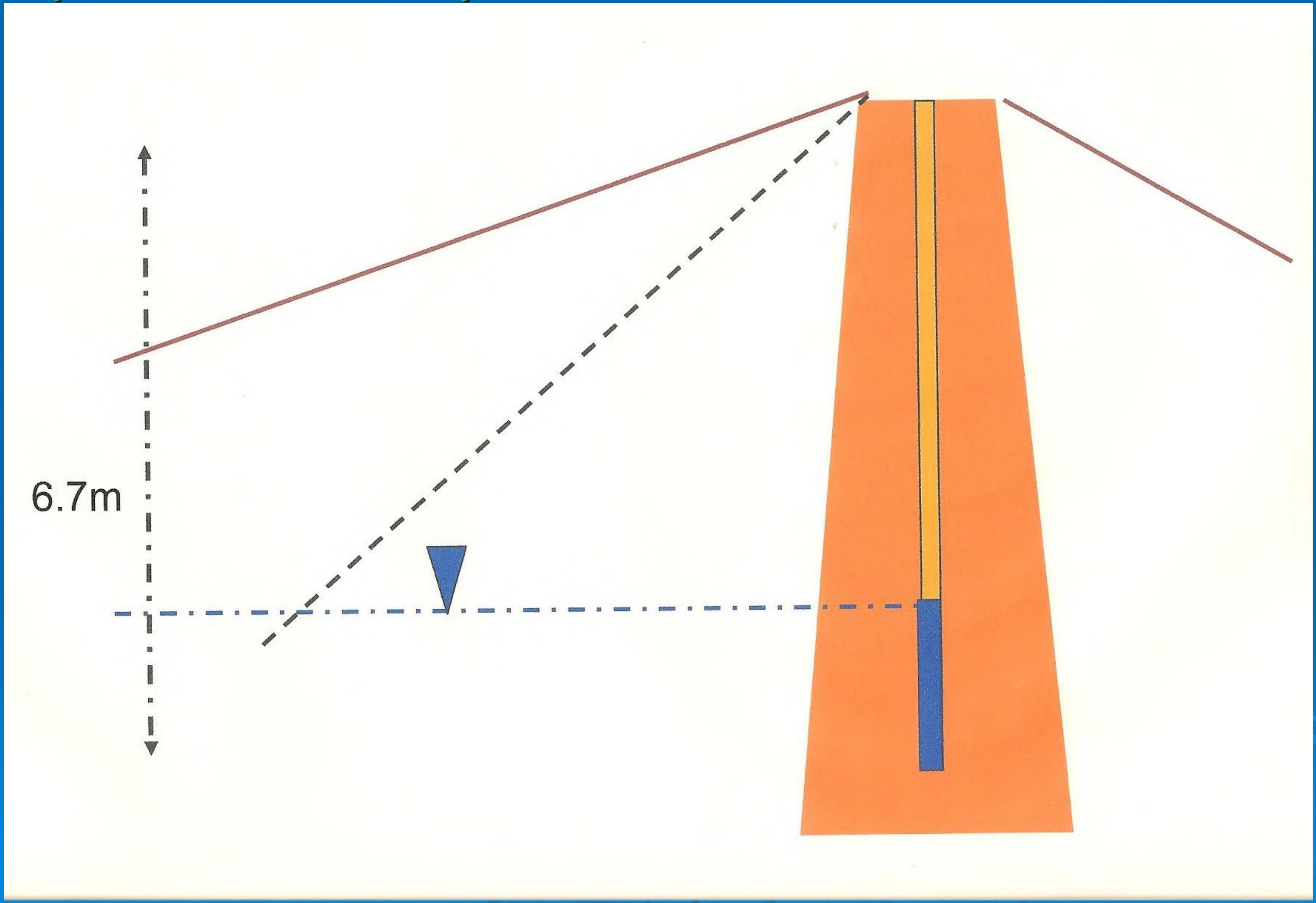
Ref: Flemming and Rossington (1985)

Longitudinal section





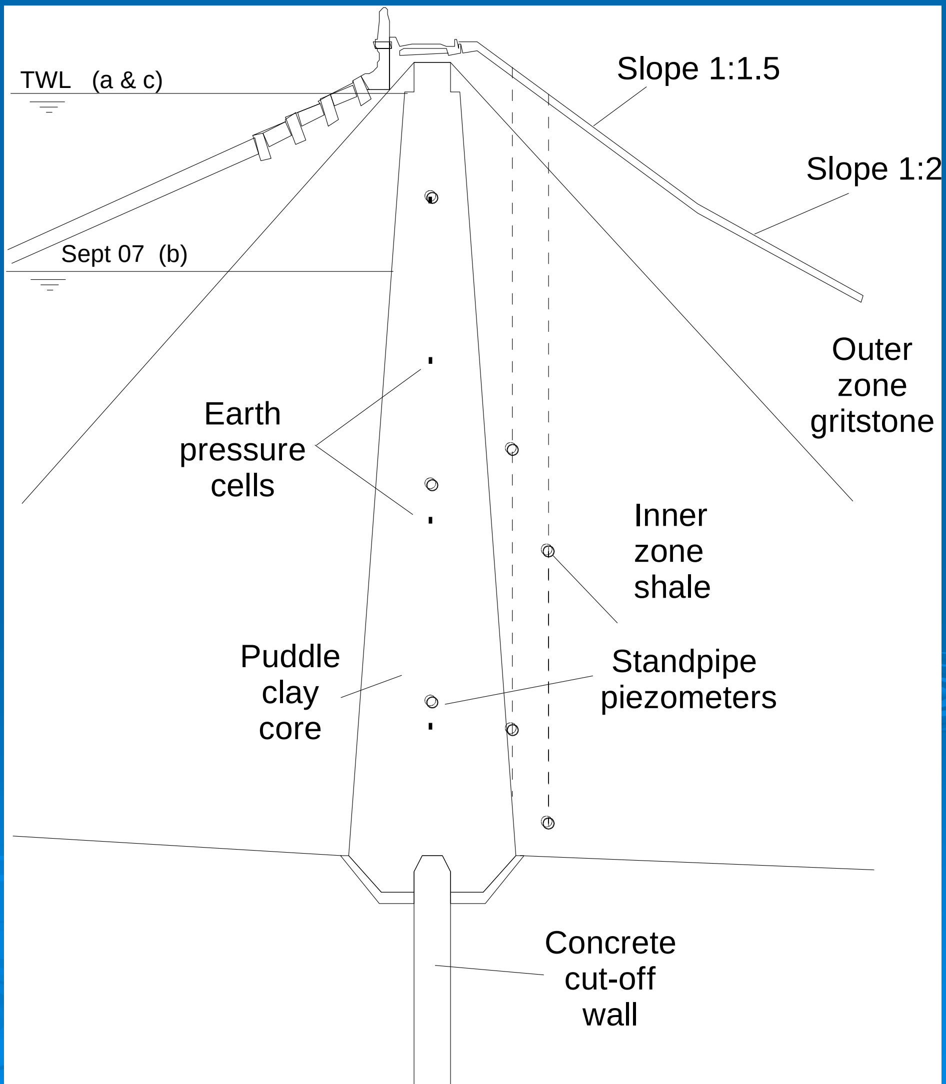
2001 – Borehole investigation for seismic assessment reveals connection between core and reservoir at 6.7m depth in the central part of the dam.



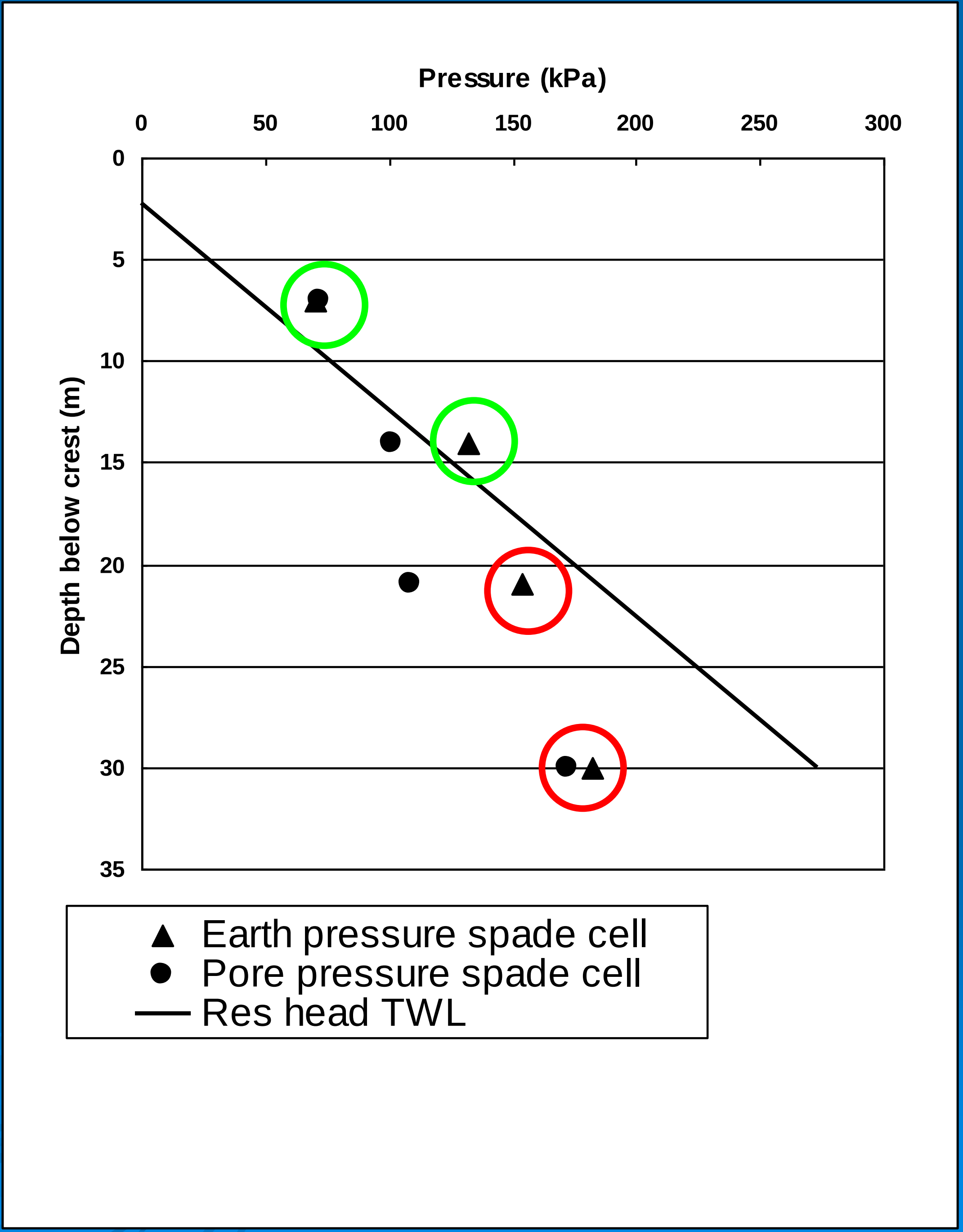
2004 Susceptibility to Hydraulic Fracture Investigation

Concerns that there was leakage through the core led to the in-situ stresses being investigated. The incident in 1983 influenced the decision to undertake further investigations

2004 – BRE installed push-in pressure cells to measure total earth pressures and pore pressures.



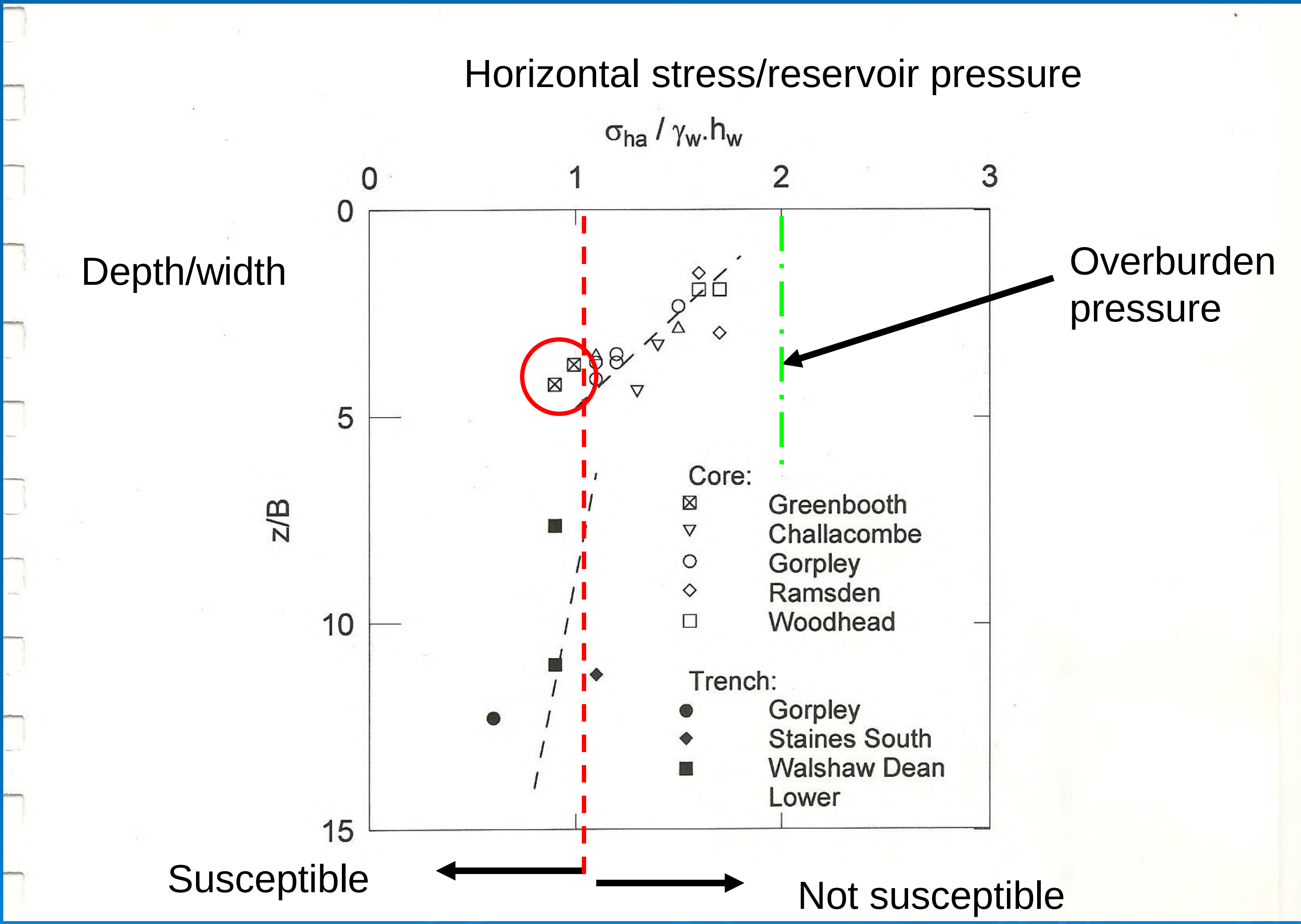
Pressure cell observations September 2004 with reservoir at TWL, six months after installation.



Findings

At 30m and 21m the measured earth pressure was significantly less than the pressure due to reservoir head. At 30m, the difference was 9m head (90kPa).

At 7m and 14m, the measured earth pressure was larger than the reservoir head.

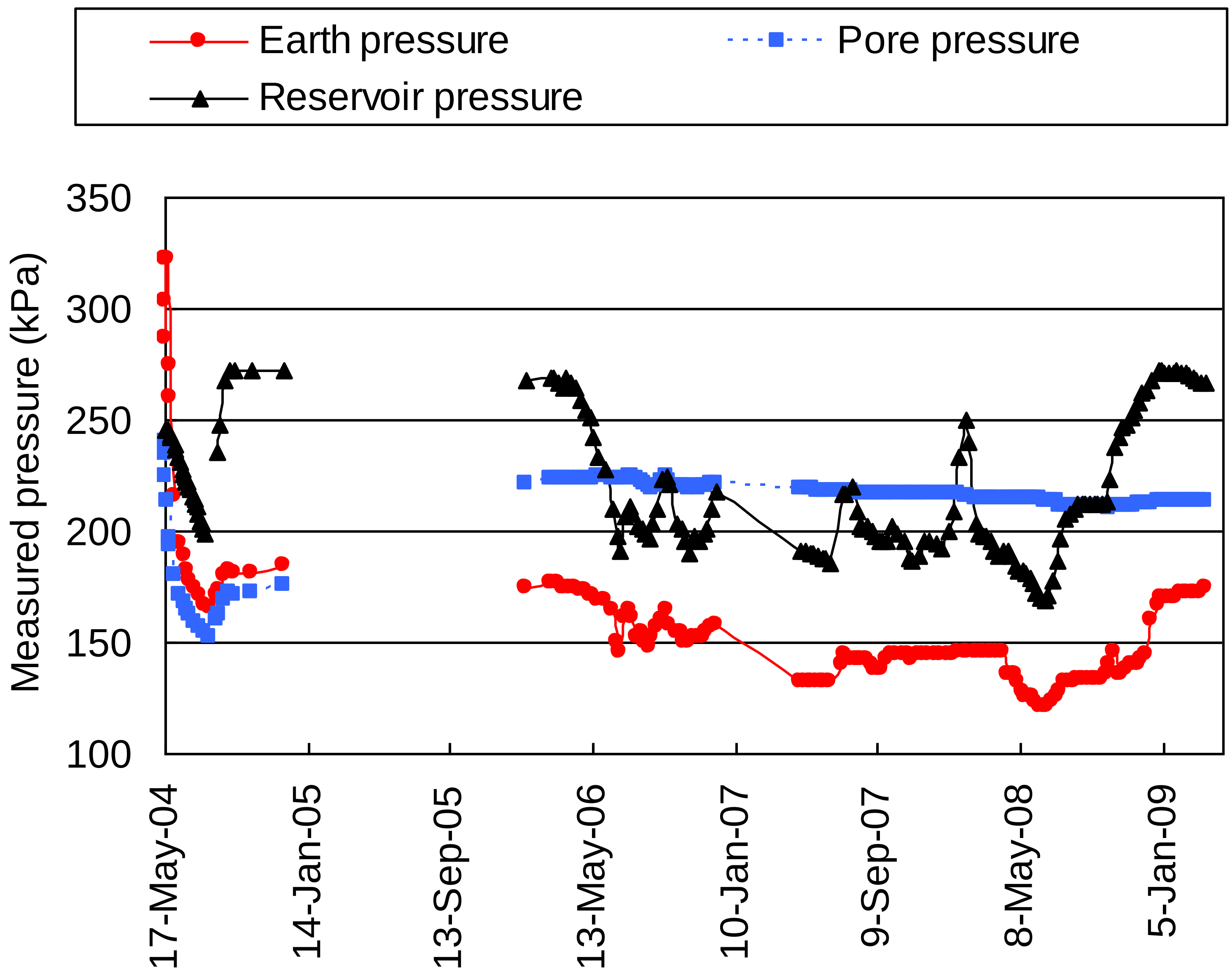


Horizontal stresses measured in puddle clay cores and cut-offs

Implication of observations

- The results therefore indicated vulnerability to hydraulic fracture at depths of 21m and 30m, but not at 7m.
- Were the results due to instrument malfunction?
- Can we believe what we measure?
- What other methods were available to verify these findings? – critical pressure tests

Borehole 411 - 30m depth



Objectives of 2007 Investigation

- Undertake critical pressure tests in standpipe piezometers in the clay core to assess if the core is vulnerable to hydraulic fracture
- Undertake permeability tests in the core during drilling and in the standpipe piezometers
- Obtain pore water pressures in the core
- Sample clay core
- Undertake erodibility tests
- Characterise properties of clay; strength, plasticity, grading
- Identify any anomalies

Ulley
June 2007

Clay core – observations during drilling

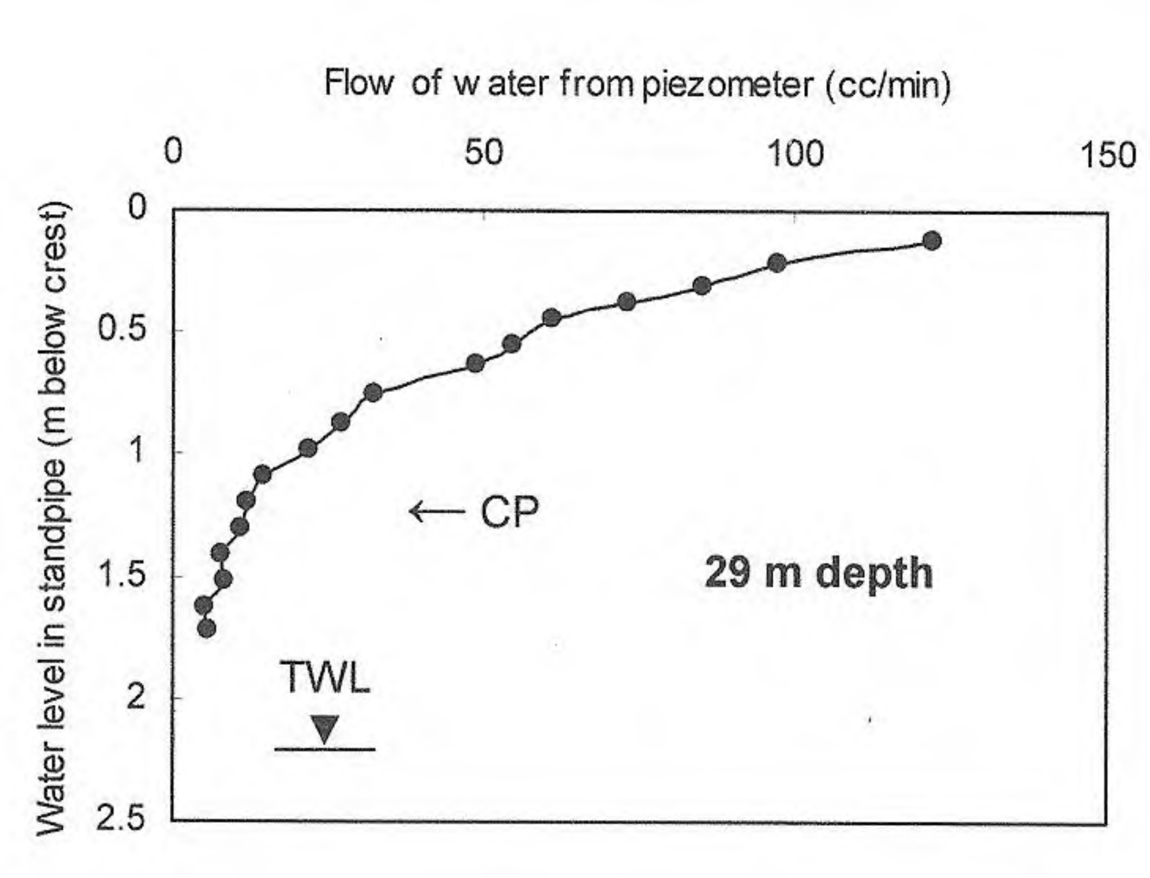
- Very soft to soft well graded, silty sandy, slightly gravelly CLAY of low to intermediate plasticity
- Hand vane gave shear; between 15 and 40 kPa
- Core recovery very variable. Depth 4m to 14m: 0.35 to 0.4m. Below 21m, the plastic inner sampler tube became stuck due to sand or silt.
- Permeability tests indicated low values, no evidence of hydraulic fracture indicated by loss of water.


C
20.5-21.2

Sample disturbance

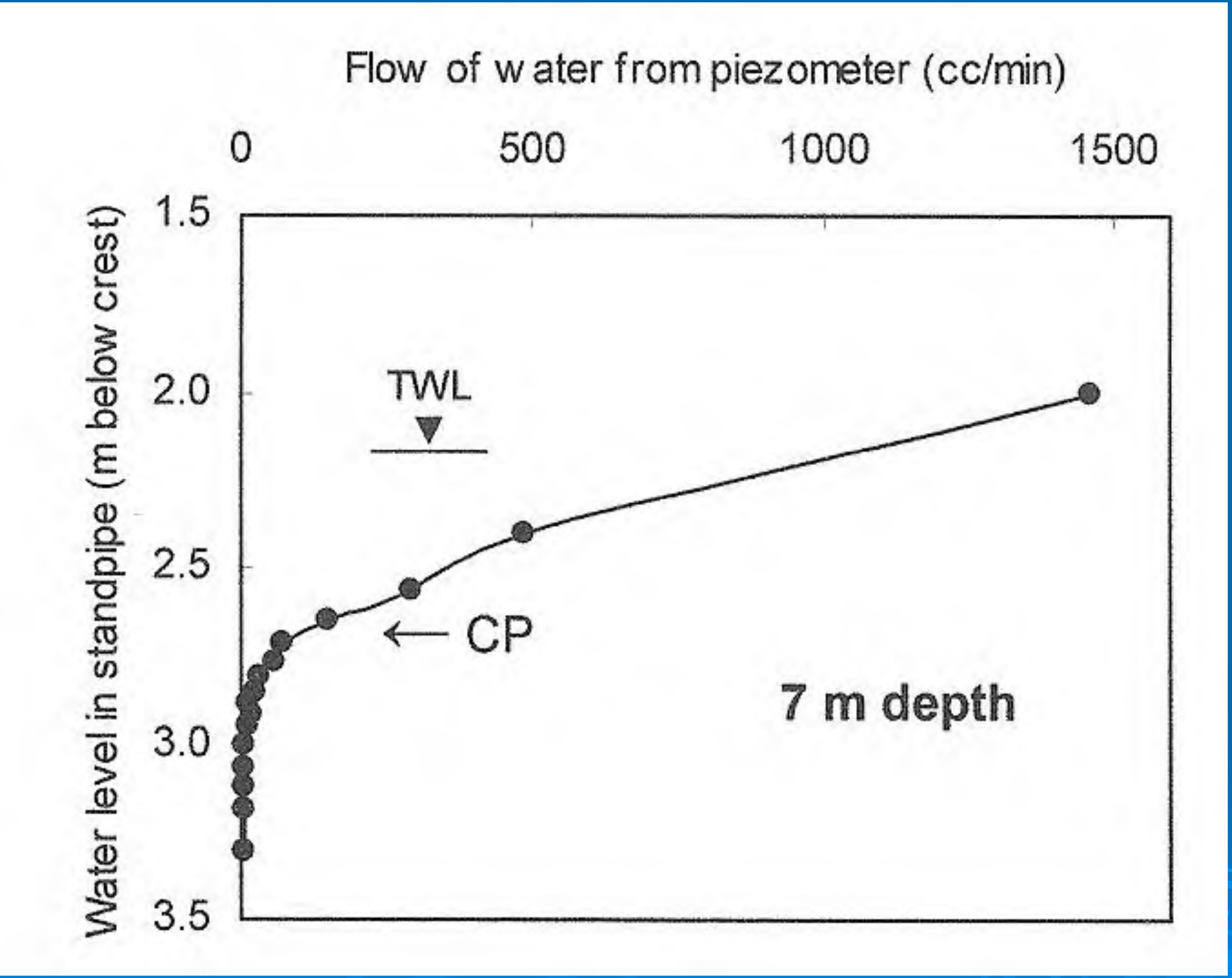
Piezometer Installation

Critical pressure tests at 29m



The tests suggest that the clay core is unlikely to be susceptible to hydraulic fracture at 21 and 29m depth

Critical pressure tests at 7m



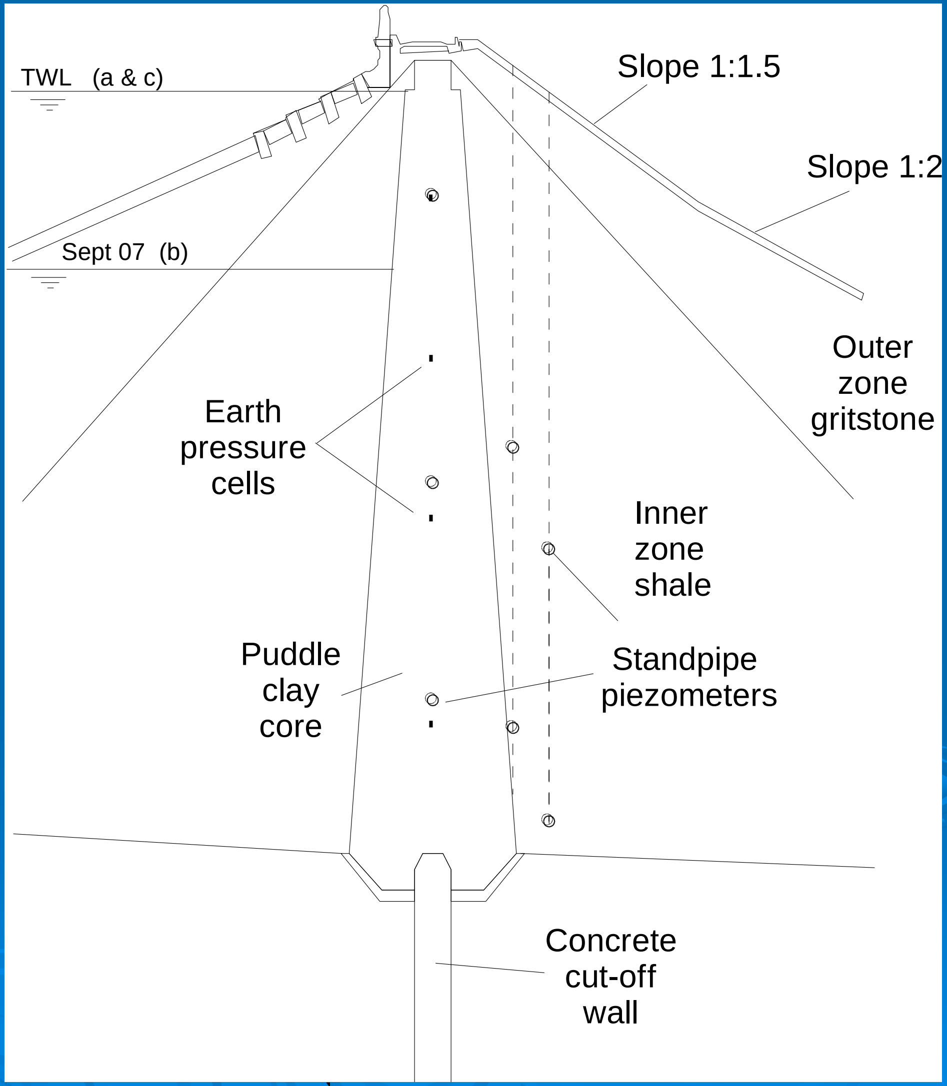
The tests suggest that the clay core could be susceptible to hydraulic fracture 7m depth

Erosion resistance Tests

Cylinder dispersion test: Generally non-dispersive
Pinhole test (Sherrard et al): Three tests: all non dispersive
Double dispersion test: Implies flocculating conditions do not exist

Downstream fill investigation

- Identify any evidence of leakage
- Measure any pore pressures in the fill
- Measure in-situ permeability for filter assessment (Perfect Filter Method, after Vaughan)
- Assess filter properties from gradings of samples (Critical Filter Method, after Sherard)

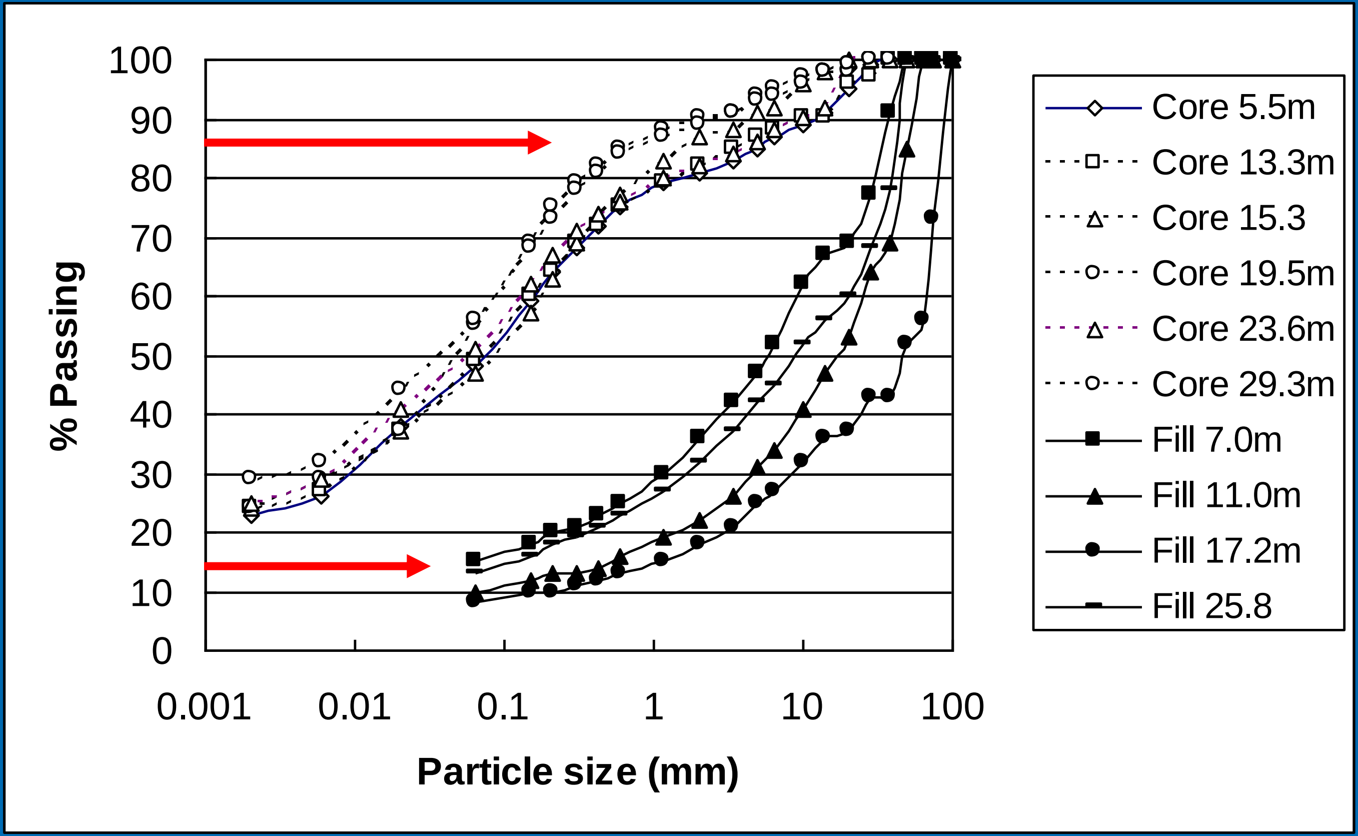


Downstream fill

- Upper 6m appeared to have high clay and low permeability
- Below 6m very free draining with permeability larger than 2×10^{-4} m/s
- Minor water strikes at 17, 26, and 29 m below crest level
- No pore pressure in the piezometers

Downstream fill

Particle size ratios for filters



(D15)f/(D85)c

Recommended	< 5
Average	0.12
Least favourable	2.00

Conclusions

- Inconclusive evidence on hydraulic fracture
- Possible that Greenbooth is leaking by hydraulic fracture, but many dams leak
- Core is a low plasticity clay, likely to erode
- No surface evidence of settlement
- No or very small pore pressure in downstream fill

The End