Long-term stress measurements in the clay cores of storage reservoir embankments

K S WATTS, Building Research Establishment Ltd, Watford, UK.
A KILBY, Thames Water plc, London, UK
J A CHARLES, Building Research Establishment Ltd, Watford, UK.

SYNOPSIS. In 1987 push-in spade-shaped earth pressure cells and BRE miniature push-in earth pressure cells were installed to study stresses within the puddle clay cores of Staines South and King George VI storage reservoirs in west London. The spade cells were installed to measure horizontal stress and the miniature cells were installed to measure both horizontal and vertical stresses. In 1998 spade cells were also installed at various sections in the rolled clay cores of Queen Mother and Wraysbury reservoirs. This paper outlines the monitoring programme and briefly describes the instrumentation and installation techniques. Selected data sets demonstrate the reliability and longevity of the instrumentation. The results show that these instruments can provide valuable long-term information on stress levels within clay cores and, in particular, the effects of reservoir drawdown and refilling on the magnitude of these stress levels in relation to reservoir water pressure.

INTRODUCTION

A survey by Charles and Boden [1] of nearly 100 cases of unsatisfactory performance of embankment dams in the UK suggested that the most serious hazard for old earth dams as they age in service is associated with internal erosion. Hydraulic fracture of a clay core is one possible mechanism which can initiate internal erosion and it has been postulated that hydraulic fracture can occur if the water pressure from the reservoir exceeds the minimum total earth pressure acting on a transverse plane within the body of the core. The state of stress within clay cores is therefore of considerable interest. Charles [2] has reviewed case histories of the deterioration of puddle clay cores and Charles and Watts [3] have described a programme of field measurements to examine the horizontal pressures within puddle clay cores and puddle-filled cut-off trenches of old earth dams.

With uniform ground conditions and a level ground surface it is usually assumed that the vertical total stress can be calculated with sufficient accuracy by multiplying the depth below ground level (z) by the mean bulk unit weight of the soil above that depth (γ). However, there are situations where the vertical stress is significantly different from the calculated overburden pressure. An important example is where there is "arching" involving stress transfer between soils with different stiffness such as between the clay core and shoulders of an embankment dam. In such cases the vertical total stress may be significantly smaller than γz and the horizontal stress will be a complex function not only of depth and unit weight of the soil, but also of the stress-strain relation and stress history of the soil. Reliable determination of vertical and horizontal stress usually requires in-situ measurement.

INSTRUMENTATION

Two types of pressure measuring device have been installed to monitor the stresses within the cores of four embankment dams.

Spade type pressure cells

The use of push-in spade-shaped earth pressure cells (“spade cells”) in various types of clay has been described by Penman and Charles [4] and Tedd and Charles [5]. Spade cells have proved to be very simple and reliable for stress measurement although there is a tendency for them to over-read even when the excess pore pressure set up during installation has dissipated. The amount by which spade cells over-read has been investigated and a simple empirical correction of half the undrained shear strength ($0.5c_u$) has been proposed by Tedd and Charles [5]. Ryley and Carder [6] have found that a larger correction is needed where c_u >150 kN/m^2 but this is of no significance for the work reported in this paper.

The spade cells used in the investigations were manufactured by Soil Instruments Ltd. and consist of an oil filled steel envelope approximately 200mm long x 100mm wide and 6mm thick. Each spade cell incorporates a piezometer above the pressure cell and the pressures are measured by pneumatic transducers.

Installation of the cells was accomplished by pushing the spade cell about 1m beyond the bottom of a vertical borehole and all the cells were aligned to measure horizontal stress along the axis of the dam (σ_{ha}). Several weeks had to elapse after installation before the decay of the excess pressures, which were generated by pushing the cells into the clay, was complete.

BRE miniature pressure cells

Cells pushed into the soil from the bottom of vertical boreholes can only be aligned to measure horizontal stress. In the situations where the measurement of vertical stress is required, a vertical borehole may provide the only access for in-situ measurement. The BRE push-in miniature earth pressure cell (“miniature cell”) is designed to be jacked horizontally into soft clay from a vertical 150mm diameter borehole.

The miniature cell consists of a 2.4mm thick oil filled envelope attached to a wedge shaped slim body. It has a measuring area 44mm in diameter, an overall length of 115mm and a maximum body thickness of 20mm in the direction of stress measurement. The miniature pressure cell operates on similar principles to the larger spade cells.

Miniature cells are installed using a special placing device which is lowered down a vertical borehole. Cells are pushed horizontally about 450mm beyond the borehole wall and multiple installations can be carried out at different elevations within a single borehole. The cell can be pushed into the undisturbed soil with an attitude to measure either vertical stress or horizontal stress. The system has been described by Watts and Charles [7] and Watts [8].

It has been found that, generally, shorter times can be allowed after the installation of miniature cells for the dissipation of excess pressures than for the larger spade cells. Generally the correction for over-read is smaller than that required for a spade cell. No corrections have been applied to the data presented in this paper for spade or miniature type cells.

PROGRAMME OF FIELD MEASUREMENTS

The study of stresses within the puddle clay cores of King George VI and Staines South storage reservoirs in west London commenced in 1987. Further installations were carried out between 1991 and 1997 to investigate potential for hydraulic fracture on several sections at both dams. In 1998 instrumentation was installed in the rolled clay cores of Queen Mother and Wraysbury reservoirs, also situated in west London. All the dams comprise continuous embankments encircling non-impounding reservoirs which store water above the surrounding natural ground level.

Cross-sections of the central parts of all four embankment dams with the elevations of the pressure cells within the clay cores are shown in Figure 1. All cells are located on the centre-line of the cores. The pressures measured at, or close to, reservoir full condition at each of the dams are plotted in relation to the elevation of the cells in metres above Ordnance Datum. The

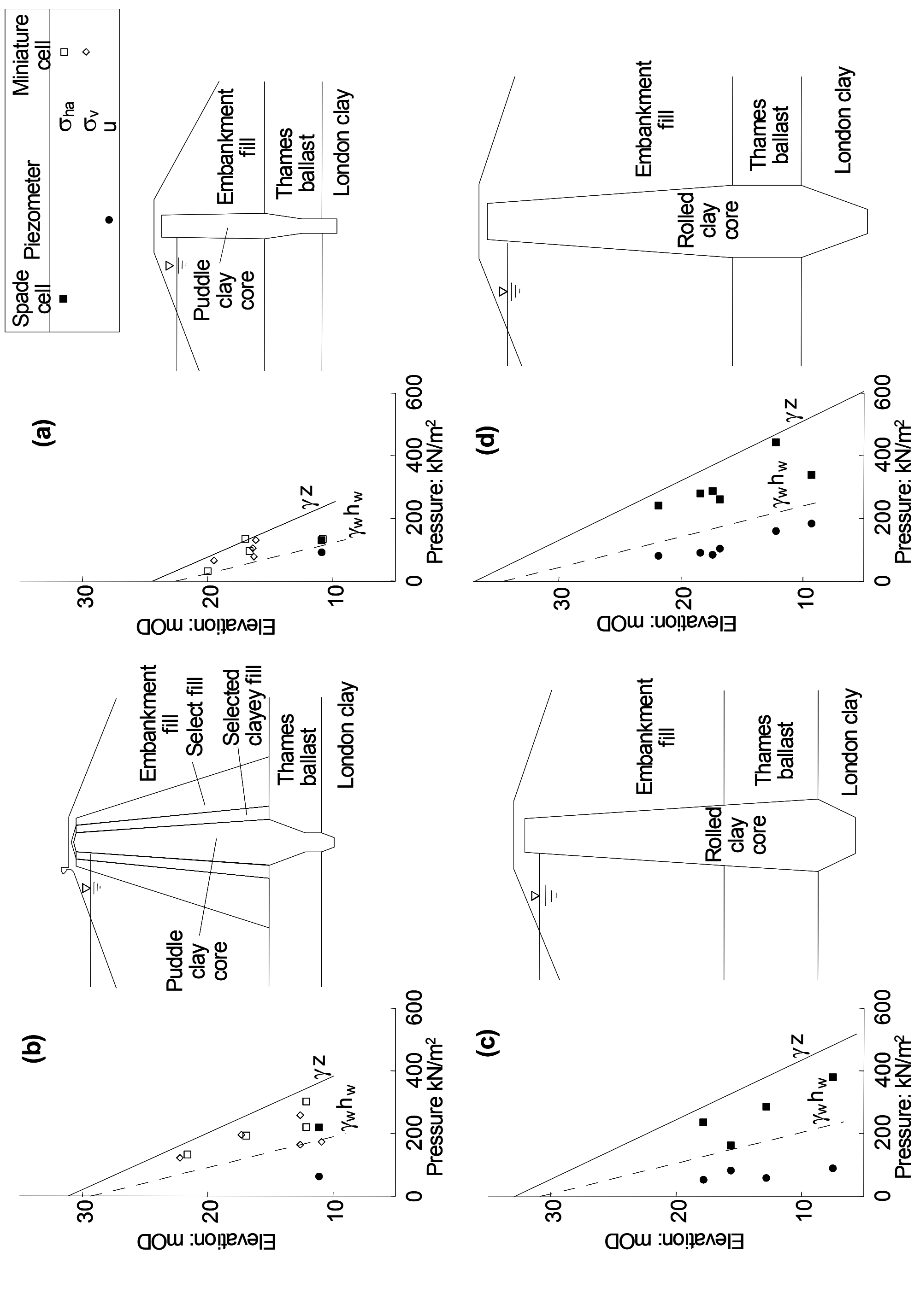

Figure 1: Pressures measured on the centre-line of the clay core at:
(a) Staines South; (b) King George VI; (c) Wraysbury; (d) Queen Mother

readings represent the equilibrium pressures measured after excess pore water pressures generated during installation had fully dissipated and therefore the individual cell readings at a particular dam were not all taken at the same time. The pressure generated by the reservoir water ($\gamma_w h_w$) on the upstream face of the core, the theoretical overburden pressure (γz) within the core and the measured pore water pressures are also shown.

STAINES SOUTH

Staines South reservoir was completed in 1903. It is part of a twin reservoir and shares a common embankment with Staines North reservoir and has a top water level approximately 3m lower than Staines North. The dam has a maximum height of 9m. The central puddle clay core extends 6m to 8m below original ground level to form a cut-off through the Thames ballast and is keyed a short way into the underlying London clay. The plasticity results of the puddle clay plot above the A-line of the plasticity chart and are classified according to BS 5930 [9] as very high plasticity (CV). Undrained shear strengths (c_u) measured from samples from the core were in the range 20-30 kN/m^2.

Miniature cells were installed in the puddle clay core at 8m below crest level to measure vertical stress and horizontal stress in the axial direction at a section where the embankment height was 9m above original ground level. Another miniature cell was installed at 5m below crest level to measure vertical stress. A spade cell was installed to measure horizontal axial stress 13.5m below the crest in the clay filled cut-off trench at the level of the boundary between Thames ballast and London clay. In 1993, a similar installation was carried out at another location comprising a spade cell at 13.6m below the crest and miniature cells to measure vertical and horizontal stresses at 8m and 5m below crest level.

The spade cell and miniature cell orientated to measure horizontal stress along the dam axis (σ_{ha}) in the deepest part of the clay cut-off are in close agreement and show pressures slightly above reservoir pressure. Data from miniature cells installed in the puddle clay at a depth of 8m below the top of the embankment are shown in Figure 2. These typical measurements demonstrate the longevity and stability of the pressure cells over a long period. The vertical stress at this position is less than the horizontal stress.

The maximum level at which the reservoir has been held has varied, but a broadly consistent pattern of earth pressure changes has been observed. The variations in vertical and horizontal pressure due to a number of major drawdown events have been monitored and the drawdowns in 1994, 1997 and 1998/99 when the reservoir was emptied are of particular interest.

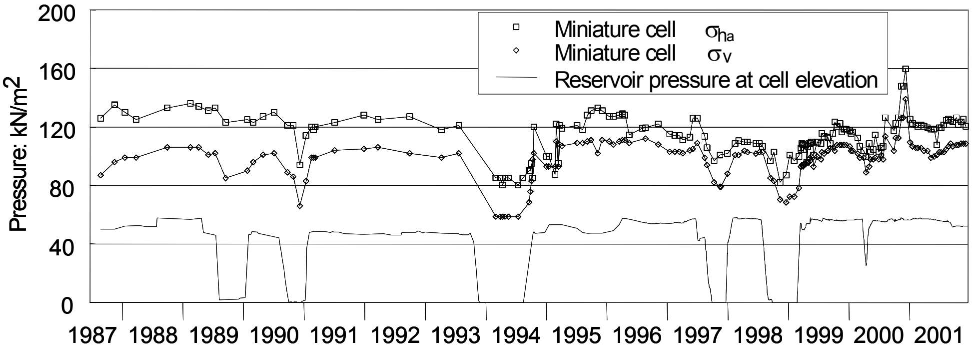

Figure 2: Measurements of vertical and horizontal pressures within the puddle clay core of Staines South at 17mOD.

On reservoir drawdown, the earth pressures have shown substantial reductions and the measured pressures have then risen rapidly in response to reservoir refilling. However, there has been some delay in returning to the pre-drawdown stress levels with final recovery in stress occurring over a period following refilling.

The anomalous peak in the data in late 2000 is more likely to be related to a common readout fault or operator error than to actual ground behaviour. There has been a general convergence of the vertical and the horizontal pressure readings since 1987, principally as a result of a steady increase in vertical stress. This pattern may be associated with the major drawdown events.

KING GEORGE VI

King George VI reservoir was completed in 1947. It has a maximum height of 17m above original ground level. The embankment is constructed of ballast excavated from the centre of the reservoir and contains zones of selected fill either side of a puddle clay core. Although slightly wider, the geometry of the cut-off through the Thames ballast is similar to that at Staines South. The plasticity results of the puddle clay plot above the A-line and vary from high (CH) to very high plasticity (CV). Undrained shear strengths of recovered samples were also in the range 20-30 kN/m^2 and were generally found to increase with depth.

In 1987 a spade cell was installed to measure horizontal stress in the axial direction at 20m below crest level in the clay filled cut-off trench. Miniature earth pressure cells were installed in adjacent boreholes to measure both vertical and axial stresses at approximately 19m and 10m below crest level. In 1991 five additional miniature cells were installed in a single borehole

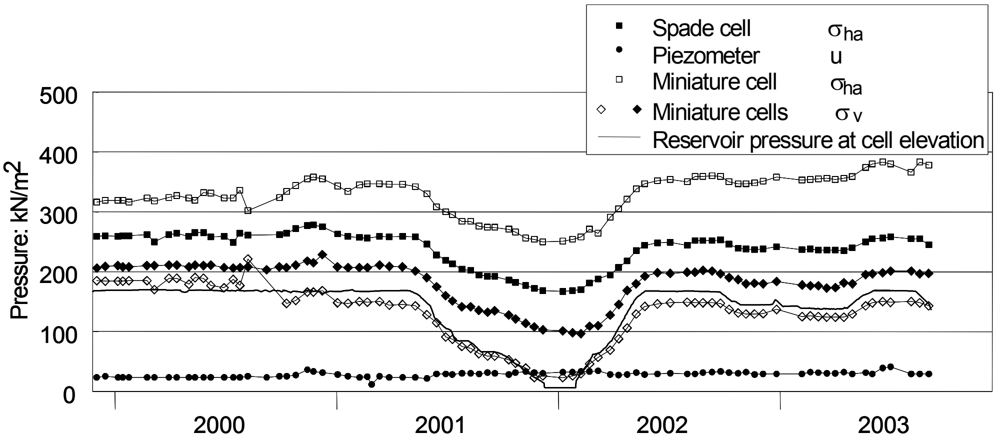

Figure 3: Measurements of vertical and horizontal pressure within the puddle clay core of King George VI at 12mOD.

close to the 1987 installations to measure vertical pressure at 20m and vertical and horizontal pressure at 19m and 14m below crest level. A further four cells were installed to measure vertical and horizontal pressure between 20m and 18m below crest level at another location in 1997.

The two miniature cells which are orientated to measure vertical stress (σ_v) in the clay filled cut-off trench have consistently measured reservoir pressure since, or shortly after, the time of installation. One cell encountered some granular material during installation and did not register excess pressures during or after installation.

In Figure 3 the pressures measured by a spade cell with piezometer and three of the miniature cells installed in adjacent boreholes at an average depth of 19m below top of embankment are plotted along with the reservoir pressure at that elevation. The figure covers the period from 2000 to 2003, during which the reservoir underwent a major drawdown and was empty for about 1 month during the winter 2001/02. The response to such an operational event indicated by the short-term detailed observations illustrates the benefits of instrument stability and regular monitoring.

The profile of pressure reduction measured by the cells closely follows the reservoir drawdown. The measured earth pressures generally recovered to values similar to those before drawdown, but the horizontal pressure (σ_{ha}) measured by a miniature cell located about 1m above the spade cell has continued a rising trend which was evident before the drawdown. All the cells showed some small time delay in reaching a maximum pressure reading some time after the maximum reservoir level had been fully reinstated.

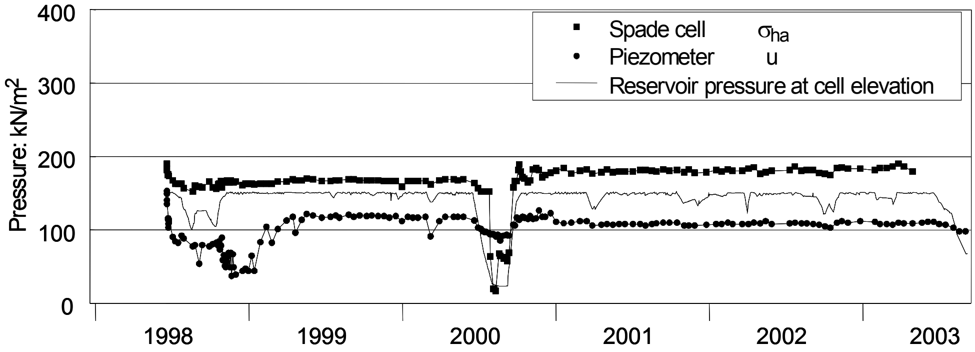

Figure 4: Measurement of horizontal pressure within the rolled clay core of Wraysbury at 15.6mOD.

WRAYSBURY

Wraysbury reservoir was constructed between 1965 and 1970 and comprises a zoned embankment with rolled clay core and gravel shoulders with clay layers within the upper part of the downstream shoulder. The embankment has a maximum height of 17m above foundation level.

The rolled clay core extends 11m below surrounding ground level to form a cut-off through the Thames ballast and keys a minimum of 3m into the underlying London clay formation. The plasticity results of the rolled clay core generally plot above the A-Line and are classed as high plasticity (CH). Water was added to the clay, which was placed to a specified undrained shear strength of about 80kN/m^2 with air voids not greater than 3% [10].

In 1998 single spade cells were installed at four locations between 15m and 25m below crest level. These installations were carried out to investigate stress levels within the core and changes in horizontal pressure in response to rapid operational changes in reservoir level.

The deepest and shallowest cells illustrated in Figure 1(c) have given remarkably stable readings since installation in 1998. The pressures measured by these cells during reservoir full conditions remained unchanged after a 7m drawdown during August and September 2000. The cell at elevation 12.8mOD has indicated a steady fall in horizontal stress σ_{ha} of about 50kPa or 5.0m water head since 1998. The cell at elevation 15.6mOD, which measured pressures close to reservoir full level after installation has shown a quite different trend as shown in Figure 4. There has been a marked and sustained rise in earth pressure at this cell after the reservoir drawdown while the piezometer at this location has measured a small but sustained fall in pore water pressure.

QUEEN MOTHER

Queen Mother (formerly known as Datchet) reservoir was constructed between 1969 and 1974 and comprises a zoned embankment with rolled clay core and gravel shoulders with clay layers within the downstream shoulder. It has a maximum height of 20m above foundation level.

Core clay properties are similar to Wraysbury. The specified placed undrained shear strength for the clay was also about 80kN/m^2 with air voids not greater than 3%[11].

In 1998 single spade cells were installed at six locations at depths between 15m and 28m below the crest. The installations were also carried out to investigate stress levels within the core and changes in horizontal pressure in response to rapid operational changes in reservoir level.

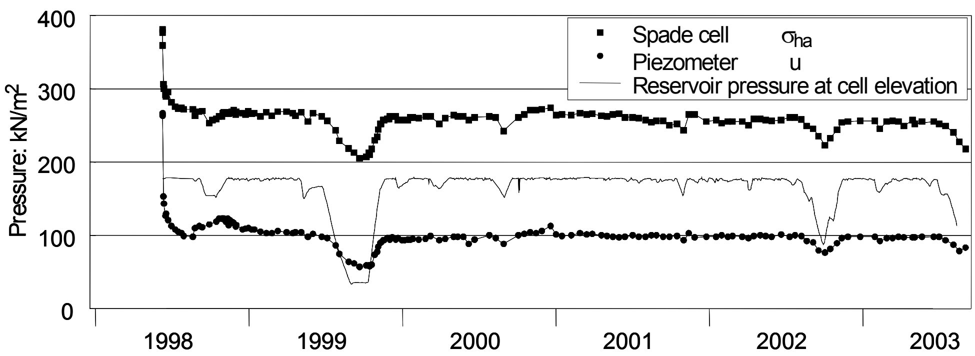

Figure 5: Measurement of horizontal pressure within the rolled clay core of Queen Mother at 17mOD.

The long-term measurements obtained from the pressure cells installed at Queen Mother indicate a rather different pattern of behaviour to that observed at Wraysbury. Figure 5 shows pressures measured by a spade cell and piezometer installed 20m below the crest of the dam. It is one of a cluster of three cells at similar depths shown in Figure 1(d). Initial readings after installation in June 1998 show the dissipation of excess pressure due to installation. The cell was installed during a period when the reservoir was at, or close to normal top water level.

Since cell installation there have been two periods when the reservoir level was reduced by a significant amount and a number of minor reductions in level have occurred over shorter time periods. The plot shows the sensitivity of the pressure cell to changes in reservoir level and hence variations in horizontal pressure within the clay core. During 1999 the reservoir level was reduced by approximately 14.5m and held at the reduced level for just over one month. This resulted in a reduction in σ_{ha} of 65 kN/m^2, equivalent to about half the reduction in reservoir pressure. This reduction was time dependent and the pressure was still falling when the reservoir level was rapidly raised. The rates of change of the earth pressure and the pore water pressure measured by the associated piezometer appear to be closely related.

There has also been a small but steady decline of about 15kN/m^2 or 1.5m head in the earth pressure measured by this cell for reservoir full conditions over the five years since installation. The measurements obtained from this cell are typical for the dam and a very similar pattern of reaction to reservoir drawdown and a steady decline in pressure is repeated for all the cells at different locations along the dam.

DISCUSSION

A considerable volume of data now exists for all the four monitored dams. The oldest instrumentation, which is in Staines South and King George VI, has provided a continuous record of pressures over a period of 16 years. The vast majority of the spade and the miniature cells have given realistic and consistent measurements throughout the monitoring period. The instruments have made possible the measurement of in-situ stress under static reservoir full conditions and with fluctuating reservoir levels.

Under static conditions with reservoir full, the earth pressures within the clay cores generally are significantly above the reservoir pressure at that particular depth. Vertical and horizontal pressures measured at similar elevations in the puddle clay cores of Staines South and King George VI are generally similar in magnitude and no consistent pattern as to a dominant direction has emerged.

The situation in the narrow clay cut-offs of puddle core dams is somewhat different. Stresses at or close to reservoir pressure have been monitored at both King George VI and Staines South.

Pressures at all elevations in the rolled clay cores at Wraysbury and Queen Mother are generally well above the reservoir pressure. One exception is a cell at Wraysbury which was installed at a predetermined elevation within a softened zone. Its elevation is coincident with the boundary between embankment fill and foundation ballast and this may be of significance.

CONCLUSIONS

1. The field measurements have demonstrated that spade cells and miniature cells can provide a reliable means of monitoring stresses in clay cores over long periods.

2. Reservoir refilling following a major drawdown is a critical time for hydraulic fracture and the instrumentation can be used to monitor stresses during this period.

3. The stress conditions in narrow clay cut-offs tend to be more adverse than in the clay cores within the embankments.

ACKNOWLEDGEMENT
The data in this paper is presented with the kind permission of Thames Water plc.

REFERENCES

1 Charles J A and Boden J B (1985) The failure of embankment dams in the United Kingdom. *Failures in earthworks*. Proceedings of symposium organized by Institution of Civil Engineers, March 1985, 181-202. Thomas Telford, London.
2 Charles J A (1990). Deterioration of clay barriers: case histories. *Clay barriers for embankment dams*. Proceedings of conference organized by Institution of Civil Engineers, October 1989, 109-129. Thomas Telford, London.
3 Charles J A and Watts K S (1982). The measurement and significance of horizontal earth pressures in the puddle clay cores of old earth dams. *Proceedings of Institution of Civil Engineers*, Part 1, **82**, Feb., 123-152.
4 Penman A D M and Charles J A (1981). Assessing the risk of hydraulic fracture in dam cores. Proceedings of 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, 1981, **1**, 457-462.
5 Tedd P and Charles J A (1983). Evaluation of push-in pressure cell results in stiff clay. Proceedings of International Symposium on In-Situ Testing, Paris, **2**, 579-584.
6 Ryley M D and Carder D (1995). The performance of push-in spade cells installed in stiff clay. *Geotechnique*, **45**, No 3, 533-539.
7 Watts K S and Charles J A (1988). In situ measurement of vertical and horizontal stress from a vertical borehole. *Geotechnique* **38**, No. 4, 619-626.
8 Watts K S (1991). Evaluation of the BRE miniature push-in pressure cell system for in situ measurement of vertical and horizontal stress from a vertical borehole. *Field measurements in Geotechnics*, Sørum (ed.), Balkema, Rotterdam, 273-282.
9 BS 5930: 1999. Code of practice for site investigations. BSI, London.
10 Reed E C (1971). Wraysbury and Datchet reservoirs. *Civil Engineering and Public Works Review*, **66**, June, pp 606-610.

11 Pawsey D B H (1976). The Queen Mother reservoir, Datchet – some aspects of its design and construction. *Ground Engineering*, **9**, October, 27-30.