Aspects of the Design of Remedial Works for Yan Yean Dam, Victoria

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Summary: The Yan Yean storage, retained by a puddle clay core embankment of 10m height, is the oldest embankment dam in Australia and formed the initial component of the Melbourne water supply. Because of its age, and some concerns about continuing displacements of the downstream face and potential piping risk, as well as seismic issues, a stabilizing fill with filters was placed on the downstream batter during 1999-2000. Whilst the original batter was constructed at 2:1, initial assessments during the design of the remedial fill indicated that a slope as benign as 5:1 could be required. The final choice of 3:1, with berm, involved lengthy considerations of clay mineralogy, the deep alluvial deposits in the foundation and their structure, and a comprehensive laboratory testing program. The links between geology, mineralogy, residual shear strength, clay structure and adopted design parameters, and the resolution of conflicting information are presented in this paper.

INTRODUCTION

Yan Yean Reservoir was constructed during 1853-7 to service the initial reticulated water supply to the city of Melbourne, and is administered by the Melbourne Water Corporation. The embankment, as originally constructed, has a relatively thick puddle clay core between earthfill shoulders, and is 9.6m high and just on 1 kilometre long between abutments, retaining a storage at design full supply level (FSL) of 33,000 ML. Batter slopes are 3:1 upstream and 2:1 downstream, while the puddle core has side slopes of 0.3:1 (Fig. 1).

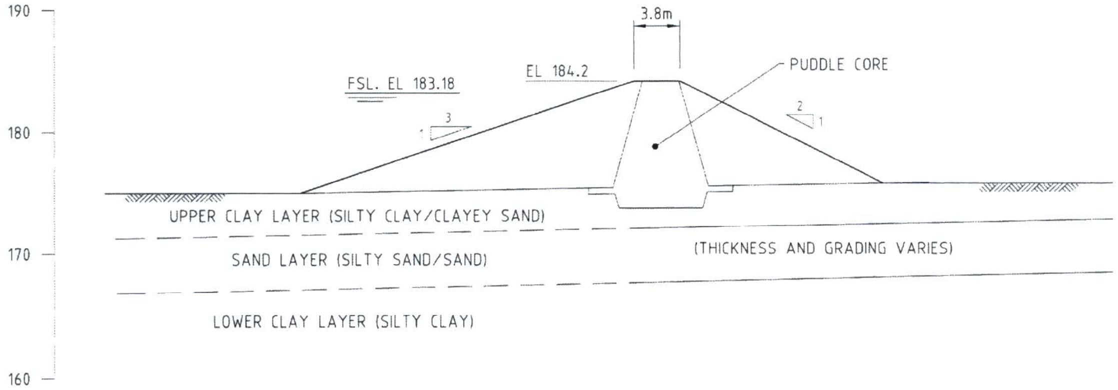

Fig 1 Yan Yean Dam as Constructed, Showing Principal Foundation Sequence

At a relatively early stage, it appears to have been necessary to add up to a metre of clayey gravel to the crest to compensate for severe (possibly 0.7m) settlement. As a result of this settlement, the design (but no longer current, for hydrological reasons) FSL had become close to the crest of the puddle core.

The most notable incident in the life of the dam was, however, the discovery in 1949 of a piping tunnel just below the upstream waterline, not far from the right abutment. Despite a major trenching exercise to trace the tunnel through the core, an outlet, frustratingly, was never found. However, tree roots (evidently originating from a line of red gums along the toe of the dam) were found in the excavations, and have generally been regarded as contributing to the event (eg, Foster et al, 2000). (The supposed role of tree roots in this event is to be pursued in a forthcoming paper, Parkin, 2003). Observations of survey points since the 1980's have indicated a significant continuing downstream movement of the downstream edge of the crest and shoulder that may be linked to the development of longitudinal crest cracks that developed about this time. These issues, together with the need to ensure compliance with current provisions for earthquake, motivated the recently completed remedial program, in which a full height chimney filter and stabilizing fill were placed against the downstream side of the dam (as detailed in Fig. 6).

The design of the remedial fill required some lengthy and complex evaluations of geotechnical parameters for the foundation materials, producing information that was often ambiguous or contradictory, and the process by which these issues were resolved is described herein. Other aspects will be reported later.

GEOLOGY

Bedrock under the Yan Yean embankment consists of interbedded sandstones and siltstones of the Silurian age Dargile (now Melbourne) Formation. These rocks were extensively folded during the late Devonian (here predominantly along a N-S axis), with some associated re-crystallisation, before being deeply eroded by the ancestral streams of the Plenty Valley. With the invasion of lava flows of the Newer Volcanics bringing about the damming and capture of the lower reaches of the Plenty River, the valley, from Pleistocene times, became infilled with alluvium to the now considerable depth of 46m at the damsite, thereby creating the Yan Yean Marsh in a tributary valley. This alluvium is mostly composed of stiff to very stiff silty clay, with minor sand lenses occurring below an upper stratum of up to 5m of clay.

In general, the Silurian shales of the Melbourne area are kaolinitic, with substantial amounts of quartz, but may in places contain significant amounts of halloysite, illite and hydrous mica (Geological Survey of Vic, 1967). The entire catchment to the Yan Yean Marsh, up to its watershed in the Sherwin Range, lies within the Silurian, with predominantly yellow podzolic soils developed thereon, so that this must be seen as the principal source of the accumulated alluvium at the damsite. By contrast, the predominant clay mineral in soils of the nearby basalt plains is calcium montmorillonite.

GEOTECHNICAL EVALUATION OF EXISTING DAM

While the testing of embankment soils and the assignment of appropriate parameters was relatively straight forward, the most complex questions, as is scarcely unusual, related to the foundation, in this case the upper clay layer, both with respect to effective stress and residual strength parameters. Peak strength was assessed from two series of 3-stage consolidated undrained (CU) triaxial tests, the later series at a lower cell pressure (<200 kPa) yielding a small increase in ϕ'. However, the non-linearity of the envelope was such that a bi-linear model was adopted, with parameters (0, 25°) up to a normal effective stress of 200 kPa, and $\phi'=12°$ thereafter (Fig. 2). The sand layer below was assigned parameters of (0, 31°).

A closer inspection of this clay was made possible by opening some six test pits along the toe of the then existing dam. This inspection revealed random fissuring at dips up to 45°, which was judged likely to reduce the mass strength from the peak value above to a fissured strength, derived as the *mean* of peak and residual strength (although this is more severe than the case of the Carsington Dam slip, referenced later).

Because of the fissuring, and the long-continuing movements, residual strength became an important issue, determining the batter slopes ultimately required. In the first instance, a series of multi-stage reversing

(3 cycle) direct shear tests were conducted, but these gave rise to some ambiguity in interpretation (Fig 3). A residual angle of 19° applied at lower stresses, but decreased significantly (by as much as 5°) at 300 kPa, while for the samples individually values of 12° to 17° were possible (though with some cohesion).

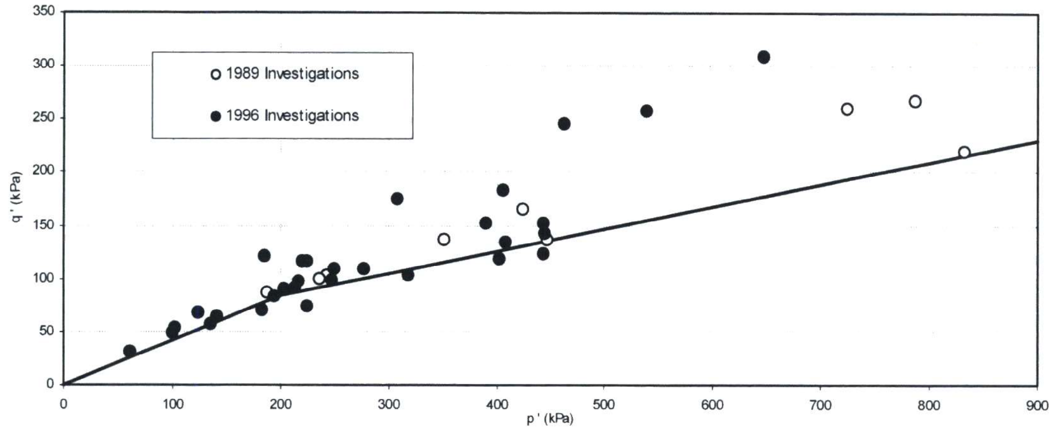

Fig. 2 Effective Stress Parameters, Upper Clay

These initial values were assessed against work by Skempton (1985a), wherein the residual friction angle (from ring shear tests and field values) is correlated against clay fraction and "colloidal activity" (A=PI/CF) (Fig 4). With clay fractions of 40 to 77% and liquid limits in the range 60-80, this gave wide-ranging predictions of ϕ_r, as shown in Table 1, which embraced a roughly similar range to that which could be read into the shear box tests. Another estimate can be made from the work of Stark and Eid (1997), who plot the *difference* between fully-softened strength and residual (ϕ'_{fs}-ϕ_r) against LL and normal effective stress, which here predicts (26-10)=16°. On the balance, a residual friction angle of ϕ_r=13° was judged, at this point, to be the most appropriate for design purposes. (It might be noted that Fig. 4 spans a range of geology from Carboniferous to Tertiary, including a Himalayan series.)

Table 1 ϕ_r from Skempton Correlation

PI	LL	Clay %	Activity	ϕ_r
-	-	42	-	11 to 15
41	59	34	1.2	14 to 18
54	72	49	1.1	10 to 14
46	64	50	0.92	10 to 14
57	80	77	0. 4	9 to 13
42	58	26	1.6	17 to 23

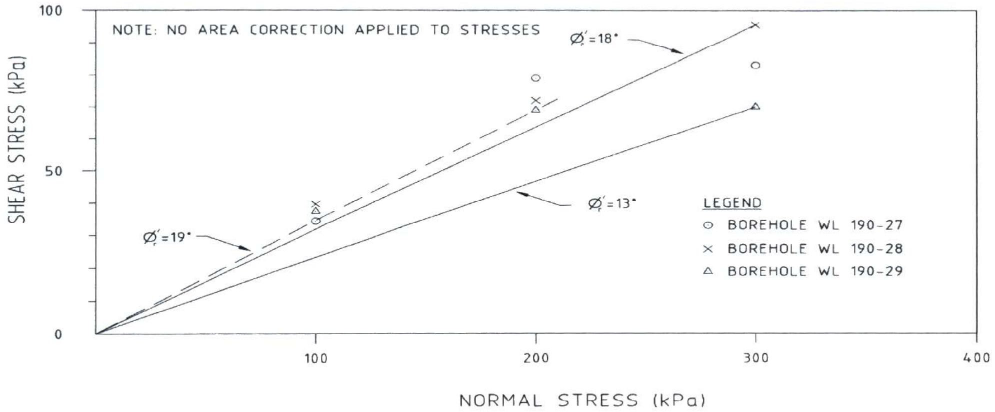

Fig. 3 Reversing Direct Shear Tests, Series 1

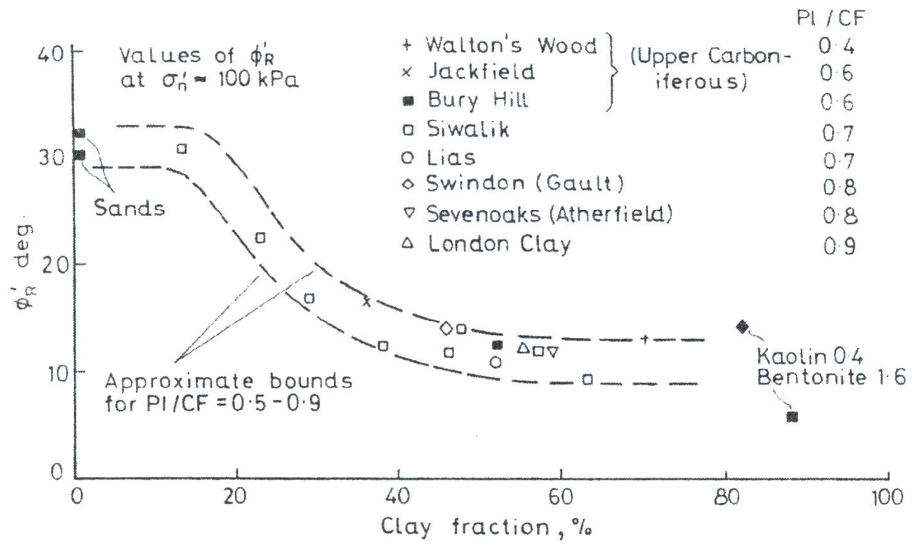

Fig. 4 Residual Strength from Tests on Sand, Kaolin and Bentonite (Skempton, 1985a)

One not unusual problem of this investigation is that some of the samples returned a residual strength that exceeds peak strength. While the test laboratory could offer no explanation for this, it added weight to the decision to adopt a residual strength in the lower part of the spectrum.

For these parameters, the static stability of the then existing dam was found to be marginal (safety factor, F close to 1), which could be consistent with the continuing (and increasing) downstream movements of the downstream batter since 1986. There was, however, also an opposing view that the movement could be shrink-swell related, as there was no evidence of movement on the upstream edge of the crest, or longitudinal cracking, to suggest a slip could be daylighting there. Whichever way, it was essential that the stability of the dam should be assured, which would necessarily require stabilizing action.

REMEDIAL WORKS – INITIAL ARRANGEMENT

Because of lingering concerns about a high smectite content in the foundation, which could take ϕ_r as low as 10°, it was initially proposed to construct a wide berm of rockfill at EL 180 over filters, with a 5:1 batter (or a 4:1 batter if ϕ_r could be taken as 13°) (Fig. 5). However, in the absence of a conventional filter in the original structure, it was further recommended, upon review, that the chimney filter should be continued up to full height, with a covering fill, in order to intercept any potential piping path and as a defence against any transverse fracture that might be induced by seismic loading. Liquefaction of the sandy zone was not considered a problem because of its confinement, but the stabilizing fill would also serve to reduce possible dynamic settlement.

INVESTIGATIONS OF CLAY MINERALOGY

On the basis of index properties determined during initial (1989-90) studies, the upper foundation soils, were classified as CH, plotting well above the A line and close to the U line of Holtz and Kovacs, (1981), from which it was concluded that smectite (montmorillonite) would be the dominant clay mineral, to perhaps as much as 80%. This suggested that the residual friction angle was likely to be around 10-12°, with major implications for the selection of a stable slope. In fact, the residual friction angle for a *pure* smectite can, according to Skempton (1985a), be as low as 5° (or 7° for the East Abbotsford slide, Smith and Salt, 1988), but rising significantly with silt/sand content.

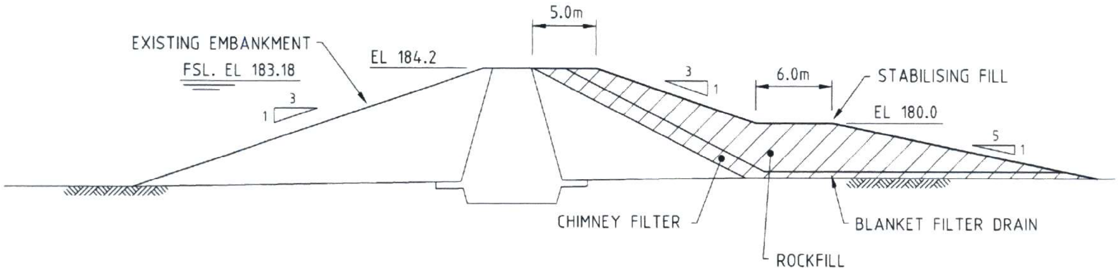

Fig 5 Initial Concept of Remedial Works

It was therefore deemed appropriate to commission a mineralogical analysis of the upper clay by X-ray Diffraction (XRD). An initial report indicated that the clay was predominantly composed of fine quartz (55%), with 20% kaolinite, 5% smectite and minor muscovite. However, because of the unusual diffraction characteristics of the smectite, the assessment was pursued further, supported by computer modeling, with a very different outcome. This indicated 45% smectite, with minor muscovite (4%) and zero kaolinite. This could be taken to support the earlier assessment and the residual friction parameter derived therefrom, but a variation of this order was disturbing, to say the least.

The problem appeared to arise from the clay crystals being small and poorly formed, with associated amorphous matter, as revealed by electron micrograph, putting them in a class of *poorly diffracting clays* that do not respond well to XRD. In particular, they failed to show the principal 001 reflection peak (15Å) for smectite, whose presence was *inferred* from computer modeling on subsidiary peaks. This uncertainty called for further examination via other avenues, including cation exchange capacity (CEC), and possibly Differential Thermal Analysis (DTA), which could be less dependent on crystal abnormalities.

While a smectite content of 45% would have major implications for slope design, all other indicators pointed to this being improbable, being not reflected in the LL (40-70) and geological setting. Accordingly, further samples were sent to another laboratory, which elected to use the XRD method again. The "clay" components (<2μm) were extracted by sedimentation for use in the XRD, with *ultrafine* particles (<0.2μm) being found to make up about a quarter of the total substance.

For mineralogical determination, analyses were performed on *randomly oriented* powder samples, and on (vacuum) *aligned* samples of the normal and ultrafine fractions. The first of these indicated clear peaks for kaolinite and illite, and a subsidiary peak (4.46Å) for smectite (with the principal 001 peak *again absent*), plus minor peaks for some inert minerals. The oriented sample showed, in addition to kaolinite and illite, an 18Å peak that is apparently indicative of an *interstratified* smectite. While not stated by the laboratory, this is thought to account for the absence of the normal smectite peak, and could also indicate that there is relatively little free smectite present. The ultrafine fraction contained rather more smectite, as could be expected, with up to 40% determined as being inter-stratified with illite.

Cation exchange capacity was determined by X-ray fluorescence spectrometry, yielding a representative value of 30c.mol/kg, a figure that is typical of illite and well below that of smectite (80-150). This further diminished the potential significance of smectite for this project.

On a quantitative analysis by XRD of the <2μm fraction (of which about 60% is ultrafine), clay minerals made up only about 20% (roughly equal kaolinite and illite/smectite), the balance being predominantly quartz, with some mica and goethite, making an interesting comparison with earlier geology and the initial report on clay mineralogy. Free smectite was not identified, in sharp contrast with the earlier assessment. In terms of residual strength, it was therefore concluded that there is little smectite present in the form familiar to geotechnical engineers, and that the inter-layered form is likely to have quite different properties. It also appears that the "clay fraction" cannot be accorded its usual significance because of the substantial component of inert material extending down even into ultrafine sizes.

FURTHER RESIDUAL SHEAR TESTING

Because the initial studies were inconclusive, a follow-up program of reversing shear box tests was undertaken. However, despite particular care, this program returned an unexpectedly high result of ϕ_r=26°, as against peak parameters of 21 kPa and 27°), which could not be reconciled with clay contents in the range of 40-50% (although note the difficulty of interpreting "clay fraction" above) and almost zero sand. This was deemed inappropriate for use in remedial design.

From a literature survey of Victorian Siluro-Devonian and other similar soils, it was found that residual strength is generally focused around 13 to 15°, with associated cohesions of ~15 kPa, ranging up to 19° back-figured on the Howletts Road slide (in Jurassic at Yallourn North, McKinley and Raisbeck, 1988). Elsewhere, values of 13° have been reported on materials containing *some* smectite, including inter-seam clay from Morwell (Cullen and Donald, 1971) and the Hallam clay pit (Piper, 1988). Whilst it is a common practice to disregard cohesion c' in effective stress stability analysis, this need *not necessarily* apply to the residual state, where the case for a non-zero c_r is supported both experimentally and by back-analysis of failed slopes (Chandler and Skempton, 1974). Correlations between ϕ_r and LL are also popular in literature, and that of Mesri et al. (1986) predicts ϕ_r=16° for LL=60% at Yan Yean.

An important issue in the papers by Skempton and others on the subject of long-term slope stability is the extent to which shear strength will degenerate from its peak at the *fully-softened state* towards residual. In the well publicized case of Carsington Dam (Skempton, 1985b), the strength drop was only 40% (by back-figuring), and it would appear to be the normal situation for long-term slips in the UK to fail *well above* residual. In fact, this slide occurred in a yellow clay possibly not dissimilar to Yan Yean, with LL 75%, clay fraction 62% and shear tests giving c_r=10 kPa and ϕ_r=12°. (The extent to which slip surfaces are influenced by per-existing defects, upon which a combination of residual and fully softened strength may apply, has been recently explored in depth by Mesri and Shahien, 2003.)

At this point, it was felt appropriate to proceed with a set of ring shear tests (in a Bromhead machine) on a sieved fine fraction of silt and clay (passing 150μm). This produced residuals of 27° and 29.5°, higher than anything previous, but it is SMEC's view that this can be related to the misleading nature of the "clay fraction" in this case, caused by a significant amount of inert material in the ultra-fine range.

In a final appraisal (by Professor R Fell), ϕ_r=16° was considered justifiable for the most plastic samples (increasing to as much as 28° for low plasticity). From stability analysis, it was found that there would be no realizable benefit from any higher value of ϕ_r (which might well be available), and the matter was settled at this figure.

REVISED DESIGN OF REMEDIAL WORKS

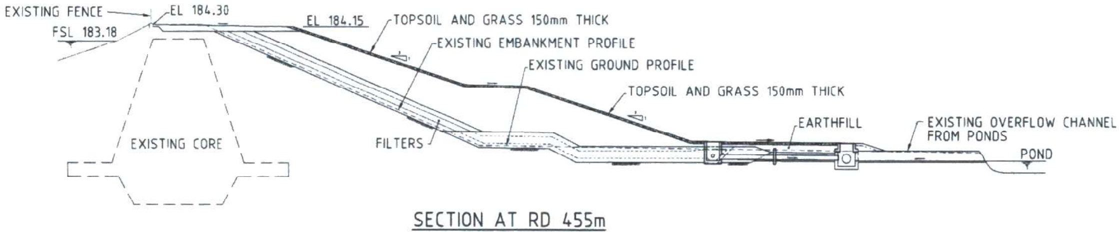

Fig. 6 Final Arrangement of Remedial Fill, with 3:1 Batters and Berm

Upon resolution of the residual strength issue, a final design was prepared, as in Fig. 6, with adopted batters of 3:1 and 3m berm, and a full height 3-component filter. A feature that would be somewhat unusual is the decision to construct the filter in fifteen separate compartments, so that any leakage that might develop at any time can be traced to a specific segment of the dam. The covering fill was amended to earthfill, to be won from a new borrow area in alluvium, just downstream of the existing pond system and extending this wetland feature.

Because of the possible involvement of tree roots in the 1949 piping incident, and the remaining trees close to the toe of the dam, areas of disturbed ground and rooty material were excavated and backfilled to filter profile level with 2C filter (akin to road base). The three-component drainage blanket (fine/coarse/fine, 2A/2B/2A) was placed over this, draining out southwards to the existing spillway discharge channel.

CONCLUSIONS

This paper has focused on one facet of the remedial measures adopted for Yan Yean Dam, as implemented in order to provide a satisfactory level of protection against piping and seismic action, and to control the continuing downstream movement and settlement. It highlights the diversity of methods utilized, the misleading results that can arise from some of them, and how those conflicts have been resolved in this case. It shows how particular soils can have unique and unexpected characteristics that may preclude the usual interpretations, such as that accorded to clay fraction. The pursuit of these matters to a conclusion resulted in a considerable saving in earthfill volume, and therefore in the cost of the project.

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REFERENCES

Chandler, R J and Skempton, A W (1974) "The design of permanent cutting slopes in fissured clays". *Geotechnique* 24:4, pp457-466.
Cullen, R M and Donald, I B (1971) "Residual strength determination in direct shear". Proceedings, *1st Autsralia-New Zealand Conference on Geomechanics*, Melbourne 1:1-10
Foster, M, Fell, R and Spannagle M (2000) "The statistics of embankment dam failures and accidents", *Canadian Geotechnical Journal* 37:5, pp1000-24.
Geological Survey of Victoria (1967) "Geology of the Melbourne District, Victoria", *Bulletin No.59, Geological Survey of Victoria* (G. Bell, Section 4-3)
Holtz,R D and Kovacs, W D (1981) *An introduction to geotechnical engineering,* (Prentice-Hall, NJ)
McKinley, T J and Raisbeck, D (1988) "Monitoring an active slide at Howletts Road, Yallourn North", Proceedings, *5th Australia-New Zealand Conference on Geomechanics, Sydney, pp475-8.*
Mesri, G and Cepada-Diaz, A F (1986) "Residual shear strength of clays and shales", *Geotechnique* 36:2, pp269-74.
Mesri, G and Shahien, M (2003) "Residual strength mobilized in first-time slope failures", *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 129:1 pp12-31.
Parkin, A K (2003) "Some observations on tree roots and piping in embankment dams", Submitted to 2003 *Annual Conference, Australian National Committee on Large Dams*, Hobart, Tasmania (October, 2003).
Piper, J P (1988) "Analysis of two failed excavated slopes", Proceedings, *5th Australia-New Zealand Conference on Geomechanics*, Sydney, pp392-7
Skempton, A W (1985a) "Residual strength of clays in landslides, folded strata and the laboratory", *Geotechnique 35*:1, pp3-18
Skempton, A W (1985b) "Geotechnical aspects of the Carsington Dam failure", Proceedings, *11th International Conference on Soil Mechanics & Foundation Engineering*, San Francisco, 5:2581-2591.
Smith, N and Salt, G (1988) "Predicting landslide mobility.....East Abbotsford Slide", Proceedings, *5th Australia-New Zealand Conference on Geomechanics*, pp567-72.
Stark, T D and Eid, H T (1997) "Slope stability analyses in stiff fissured clays", *Journal of Geotechnical & Geoenvironmental Engineering, ASCE*, 123:4, pp335-343.