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A Note on the Origin of Wet Seams in Embankment Dams

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SUMMARY Concentrated seepage horizons, or wet seams, occur in the impervious zones of many embankment dams. Their presence has traditionally been attributed to hydraulic fracture, even where observations negate hydraulic fracture as a plausible mechanism. Evidence is presented herein to show that inbuilt porous horizons often provide a more logical explanation and the adverse role of calcitic soil in the formation of such horizons is proposed.

1 INTRODUCTION

The phenomenon of concentrated leakage horizons in the impervious sections of embankment dams has been adequately documented by Sherard (1968) who proposes hydraulic fracture as the most likely origin of such features, despite a number of phenomena which he cites in direct apposition to this mechanism. For instance:-

- Trenching in the cores of failed embankments has revealed horizontal wet seams of considerable lateral extent, sometimes occurring at more than one elevation. If hydraulic fracture was responsible for their formation, a variety of fracture orientations might be expected.
- Piezometers located in wet seams, at the downstream faces of impervious cores, have recorded not only full reservoir head but also fluctuations in reservoir level without any appreciable time lag. If hydraulic fracture was responsible for such wet seams, one would expect closure of the fractures to occur when the head was severely reduced.
- A majority of leakage horizons develop during first filling of reservoirs and they also occur at embankment elevations only marginally below the (transient) reservoir water level; that is, hydraulic fracture is alleged to occur at very low heads. However, hydraulic fracture at low heads has never actually been observed.

Since a combination of wet seams, dispersive soil types, and inadequate filter protection provides a means for catastrophic dam failure, it is worth pursuing some of the above contradictions in the hypothesis of hydraulic fracture a little further, on the basis that there might well be alternative explanations for the origin for wet seams.

2 HYDRAULIC FRACTURE REVIEW

Figure 1 represents a situation with an earth core sandwiched between rockfill shoulders. In many tropical and semi-tropical environments, pore pressures at the end of construction are often low to negligible, even for moderately sized dams, and pore pressures are neglected in the initial analysis here, for simplicity.

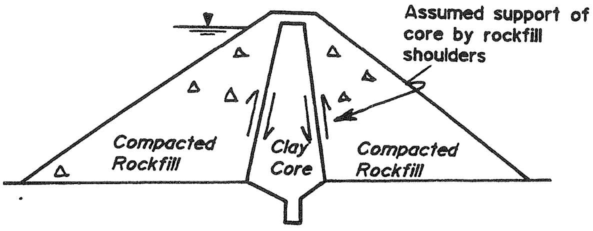

Figure 1. Rockfill dam with thin clay core.

At any point within the core, the vertical stresses at the end of construction would be given approximately by the overburden load. The horizontal stresses could be estimated using a value of Ko = 0.7, to take account of built-in compaction stresses. These values, when plotted as shown in **Figure 2**, reveal a Mohr Circle with a diameter of σ_v - σ_h lying well below the failure envelope for a typical core material.

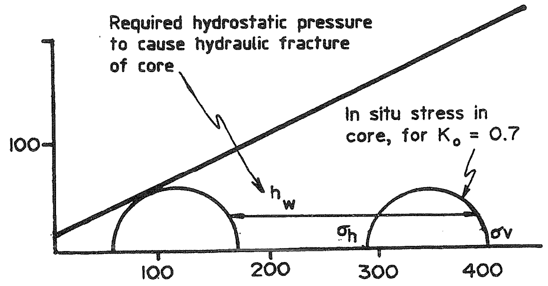

Figure 2. Stress conditions within a clay core.

Under such conditions, very high pore pressures would be required to displace the circle far enough to the left to intersect the failure envelope. In other words, hydrostatic heads in excess of the full reservoir head would appear to be necessary to initiate the process of hydraulic fracture.

This prediction is supported by a series of tests at various elevations in the Alvita Dam, Seco de Pinto et al (1985). **Figure 3** is a graphical representation of the published results, showing that hydraulic fracture of the core required pressures almost equal to the maximum overburden load. Such pore pressures would not, of course, be available from the reservoir head. The second point to be noted from the figure is that the "close-up" pressures lie only marginally below the hydraulic fracture line. In other words, cracks which are formed by hydraulic fracture seal up again when the pressures are marginally reduced. This contradicts one of the above observations made by Sherard regarding piezometers responding on a one to one basis with reservoir fluctuations.

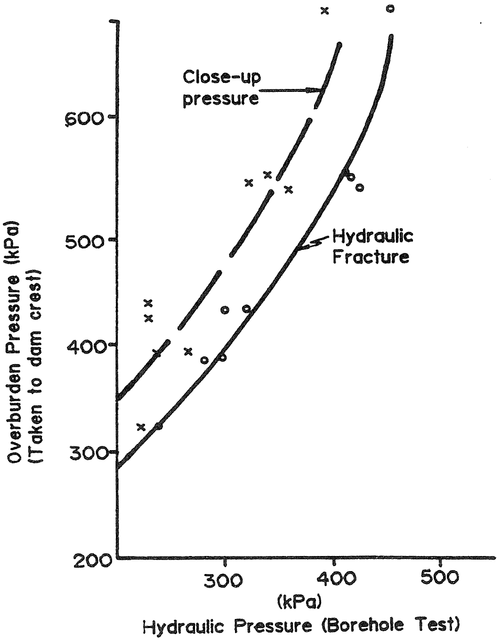

Figure 3. Hydraulic fracture tests, Alvita Dam.

A theoretical justification for hydraulic fracture in the above situation is, of course, available. If, in **Figure 1**, it is assumed that settlement of the core is inhibited by support from the rockfill shoulders, then a mechanism is available to reduce the vertical stresses in the core while the horizontal stresses remain much the same. The Mohr Circle in such a situation lies to the left of σ_h and much closer to the failure envelope of the core material. Pore pressures, or hydraulic heads invading the core, would displace the Mohr Circle even further to the left, bringing about failure. Under conditions of low vertical stresses in the core, then, hydraulic fracture at low reservoir heads is a theoretical possibility.

Whether such differential settlement of earth core dams occurs in practice is difficult to determine and has seldom been determined. It was always A.W. Bishop's contention that a well compacted earth core settled less than rockfill, but this experience might have been largely gained prior to the use of heavy compacting equipment for rockfill. However, in temperate climates, cores with high construction pore pressures are normal and these must be taken as prone to consolidation settlement after construction, making the above analysis valid.

Possibly as an extrapolation of the above approach, dams with wide cores and even homogeneous embankments are presumed to be susceptible to hydraulic fracture. The susceptibility can sometimes be related to drastic changes or steps occurring in the foundation profile. These cause the fill to settle differentially which, in turn, produces localised arching and reductions in the vertical stress. A similar analysis to that described above for narrow earth cores can be developed for this case.

While many wet seams do appear to be associated with abrupt changes in the foundation profile, e.g. Teton Dam (1980), this may not be the full story. There appear to be many more case histories where wet seams have been recorded in embankment dams without any assistance from drastic changes in the foundation profile. Moreover, as instanced at Teton Dam, the wet seams can often be traced horizontally well beyond the limits which could realistically be taken as influenced by major foundation profile asperities.

To explain such anomalies, there have been suggestions, Button (1964) and Dolezalova (1995) that, during impounding, the wetting process itself causes embankment settlement: as the lower part of the embankment becomes wet, it settles and initiates arching in the fill which still lies above the wet zone. In such circumstances, hydraulic fracture under low heads can abagin be postulated.

Since most dams which fail as a result of wet seams do so on first filling, this appears a reasonable hypothesis. However, if such a process is to occur, it implies: a) settlement of well compacted fill under (partial) saturation; and b) almost immediate saturation of an impermeable embankment during impounding. One failure on record in Queensland, Skelton (1971), occurred in a small embankment dam when the water had risen only 0.3 m against the upstream face. It is difficult to justify saturation in such a short time.

What other mechanisms are then available to account for wet seams in embankment dams, in situations where it is just not reasonable to assume that hydraulic fracture is acting? A simple answer to this would be an assumption of the presence of poorly compacted horizons within a layered fill. However, Casagrande, when investigating the failure of the 30 m high Wister Dam in Oklahoma in 1969, Sherard (ibid), discounted the possibility of poor compaction - and hence the presence of porous horizons - as a cause of failure. To judge by the subsequent literature on major dam failures since then, this avenue of porous horizons has not been actively pursued - which is perhaps surprising, human fallibility being what it is.

One reason for the reluctance to make any assumption or finding on poor compaction probably stems from the fact that such a finding involves wider issues of performance, supervision, and control testing; it can open the way to litigation. Yet, at the Wister Dam, failure came by a series of erosion tunnels at one horizon in the fill forming the closure section, **Figure 4** and, despite Casagrande's conclusion, it is suggested that erosion along a porous horizon would appear to be a more logical explanation of the failure than hydraulic fracture. Other data dealt with below are believed to support this approach.

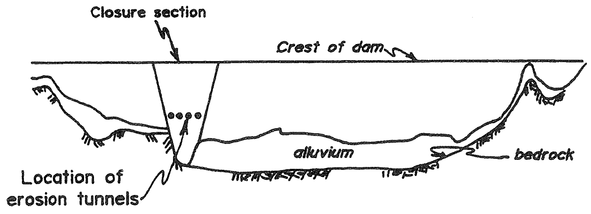

Figure 4. Piping locations in Wister Dam.

3 POROUS HORIZONS IN FILL

Porous horizons in compacted fill imply an over dry fill which is resistant to break down under compaction. In such a material, crumbs of the original soil can be preserved. Where the soil is dispersive, dry crumbs carry the dispersive characteristics into the embankment fill. The combination of dispersive behaviour and porous horizons provide sufficient conditions for the formation of wet seams and catastrophic failure.

A number of farm dam failures have been studied in research projects undertaken by the University of Queensland for the State's Water Resources Commission, Rallings (1965), Skelton (ibid), Wood (1964). **Figure 5** shows the downstream end of one such dramatic failure in the "Anderson Dam", the largest of 5 failures on the one Central Queensland property, at Monto.

Typical of such failures, this dam failed on first filling. Post-failure inspection revealed a single water-smooth erosion tunnel of approximate dimensions 300 x 600 mm, extending through the embankment at about mid height. The flow of water through this "tunnel" was sufficient to scour out the embankment to its base, producing a passage large enough to walk through upright. At the downstream outlet of this erosion tunnel, shown on the Figure, the base of sequential layers of fill could be distinguished, these being slightly more porous than the remainder of the fill. The soil was dispersive and was subsequently found to be calcitic.

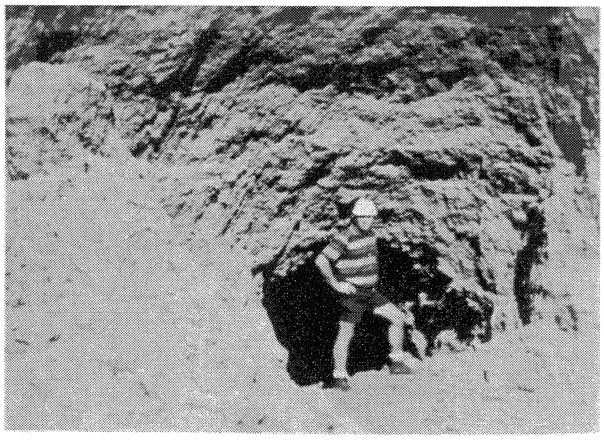

Figure 5. Downstream outlet of piping failure

Model tests made with this embankment fill illustrated the manner in which the wetting front advances preferentially along a porous horizon. Initially, mini flows occur whenever a void is encountered by the wetting front. That is, water actually flows in to fill the void. During these periods of mini flow, dispersive soil elements along the way can be transported, thereby widening the dimensions of the mini flow path up to that point. This produces a direct hydraulic connection with the reservoir. The process continues when the next void is encountered by the wetting front, which thus advances preferentially along any porous horizon. The advancement can be quite rapid. Finally, an interconnected and sometimes slightly tortuous flow path develops throughout the full dam section. Flow along this initially increases by transporting the dispersive elements away, then by simple erosion. Indeed, the initial process resembles a form of hydraulic tunnelling.

Now, the presence of porous horizons is to be expected in small earth dams compacted dry of optimum with no more than machine compaction. Porous horizons are, however, less easily justified in major dams, where fill tends to be placed closer to optimum and where greater compactive effort can reduce or even destroy an originally dispersive soil structure. For a porous horizon to occur under well controlled conditions, some added factor might be required to maintain fill in an overdry condition.

Where soil contains precipitated calcium carbonates, it is proposed that such an added factor might well be available.

Various forms of calcite/calcrete are common in soils of arid or semi-arid environments, and in soils which have experienced such environments in their recent geological history. The mineral often occurs as an amorphous precipitation, on diffuse horizons. In this form, the calcite has the ability to take up water in its internal structure. The effect of this on compacted fill is illustrated by laboratory compaction tests, **Figure 6**.

Because of this water absorption characteristic, the dry density/water content relationship of a calcite rich soil is displaced to the right of an identical soil which is calcite free. Indeed, the crossing of the zero air voids line in a laboratory compaction test is often a useful indicator of the presence of calcareous material. The laboratory optimum for a calcite rich soil can be seen as significantly higher than that obtained for an otherwise identical calcite free soil.

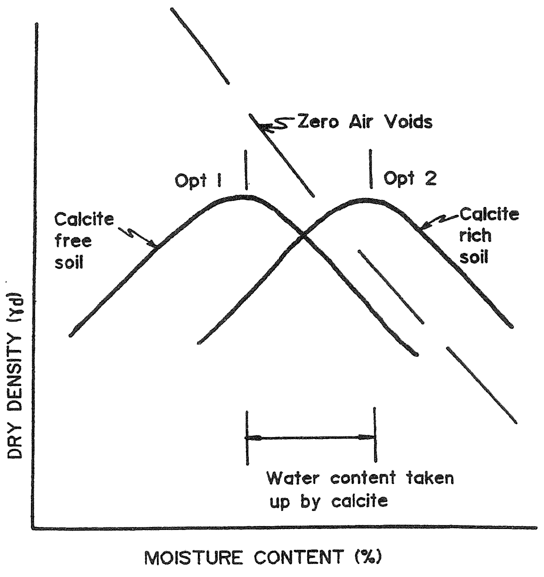

Figure 6. Effect of calcite on compaction

This effect may be transferred to a field situation.

In many semi tropical areas, fill is frequently placed dry of laboratory optimum. If, in addition to this, the borrow area(s) used for the fill contain calcite rich horizons, some of the fill will be placed additionally dry of optimum because of the water absorption by the presence of this calcite. However, as far as the laboratory testing program is concerned, this fill might be taken as being put in at an acceptable placement water content. The consequence of this will be that while control testing near the surface of a layer will pass the fill as adequate, dry crumbs of calcite rich soil may be present near the base of the same layer.

Reference to Teton Dam is relevant at this point. Here, the borrow pits contained caliche. Compaction 5 - 6% dry of optimum was used and, although visual attempts were made on site to select the less calcitic zones for the impervious section of the embankment, the success or not of this process is now difficult to gauge. What is considered significant is that wet seams in the embankment were found to contain 16% calcite, in comparison with 9% in the ambient fill. This factor was not considered of major importance to the failure by the investigating committee, but the additionally high calcite content of certain layers might well have been sufficient to tip the balance: that is, to decrease the placement water content sufficiently to allow discrete horizons of over dry fill to be incorporated in the structure. The over dry nature of this fill produced porous horizons which developed into wet seams.

A further significant factor comes out of the Teton investigation: wet seams, exposed in exploratory trenches, dribbled water and did this for some time after exposure. This indicates a storage capacity, or significant porosity, in the wet seams, and one which existed under operating conditions.

One explanation for these seams related them to snow/rain storms during construction. But even if such contaminated fill had been allowed to remain in place, any free water would surely have been largely squeezed out by the loads of later fill. Alternatively, had these seams been the result of hydraulic fracture, they should have closed up immediately the reservoir level fell during dam failure, destroying their storage capacity. Water could coneivably have been trapped in the seams on closure but, if so, it would have been trapped under full reservoir head. The presence of such high pore pressures would surely have precipitated extensive hydraulic fracturing near the upstream face of the embankment when the water load on the face was removed. This has not been recorded by in post failure investigations.

It might therefore be postulated that the wet seams in Teton Dam were simply porous horizons, probably persisting at the base of certain compacted layers due to an over dry condition in the fill. That these horizons were overly rich in calcite provides a possible explanation for the over dry condition.

This proposal raises one further problem. A porous horizon formed of dispersive soil typically causes failure of an embankment dam on first filling. This problem can, of course, be prevented by design and adequate filter protection. However, if calcite rich material is a cause of porous horizons, no filter design is adequate to cope with the situation. The calcite will pass slowly into solution and be removed. Thus, wet seams containing calcite are liable to slow deterioration over time.

Embankment dams already formed from borrow which contains precipitated calcite might therefore require periodic assessment.

For new embankments, constructed in semi arid environments, exclusion of calcitic material provides an obvious solution. This procedure, however, might not always be practicable and an arbitrary limit to calcite content is sometimes employed. In such cases, possibly the best solution for dealing with the calcite problem lies in the definition of the placement water content. Placement of the soil at or even wet of optimum should go much of the way to destroying the original soil structure and the persistence of dry soil crumbs which are integral to the development of porous horizons. In addition to control testing at the base of compacted layers, trial pits in the compacted fill allow direct inspection of the success or not of the compaction process.

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