

Flexural Slip, An Often Neglected Hazard

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SUMMARY Flexural slip seams, resulting from tectonic folding, are typically manifest as bedding plane shears in sedimentary rocks and foliation shears in metamorphic rocks. Residual or near residual strengths apply along the seams, depending on the intensity of folding and rock type. Although of great lateral extent and frequent occurrence, these seams are often missed during site investigations; when encountered, they are sometimes incorrectly diagnosed. Major redesign of dams and occasional dam failures have resulted from a non-recognition of the hazard, while landslides initiated by these features have been wrongly attributed to progressive failure. Illustrative examples are described from the literature and the writer's experience.

1 INTRODUCTION

The phenomenon of residual strength was formalised some twenty five years ago (1). The specific case largely responsible for this understanding was a slip on the M6 Motorway at Waltons Wood, U.K., a failure which was essentially a reactivated Pleistocene slide. The failure zone, located in excavation was found to be very thin; along it, the clay platlets had been rotated to an alignment sub parallel to the shearing, thereby producing minimum strength conditions.

The alignment of clay platlets, together with some migration of clay and even mineralogical breakdown on the shear zone, are well documented characteristics of the development of residual strength, both in the laboratory and field situations, (2), (3), and (4). However, a similar development in solid rock formations, by the action of tectonic folding, appears to be less widely recognised in field, although the mechanisms at work are much the same.

During folding, or flexure, there is of necessity some displacement between the various units of a geological formation, Figure 1. In a sedimentary series, this is usually taken up along the bedding planes of the more argillaceous members. In metamorphic rocks, where rapid changes in lithology might not be present, the flexural slip planes tend to be more widely spaced, but again they typically occur on discrete horizons, parallel to the foliations.

The actual amount of strength reduction involved in any flexure will be determined by the intensity of folding and on how this is accommodated by the rock mass concerned. Since the path to the residual is shortest in the direction parallel to the bedding or foliation, (5), most flexural slip seams with the same orientations will tend to have strengths at or near residual. In such cases, highly polished surfaces occur, usually with sufficient striations to indicate the direction of movement during flexure. These striations can serve to distinguish flexural slip seams from shears caused by other phenomena such as translational faults or gravity slides.

The phenomenon of residual strength is well documented in the literature, both for landslides and for

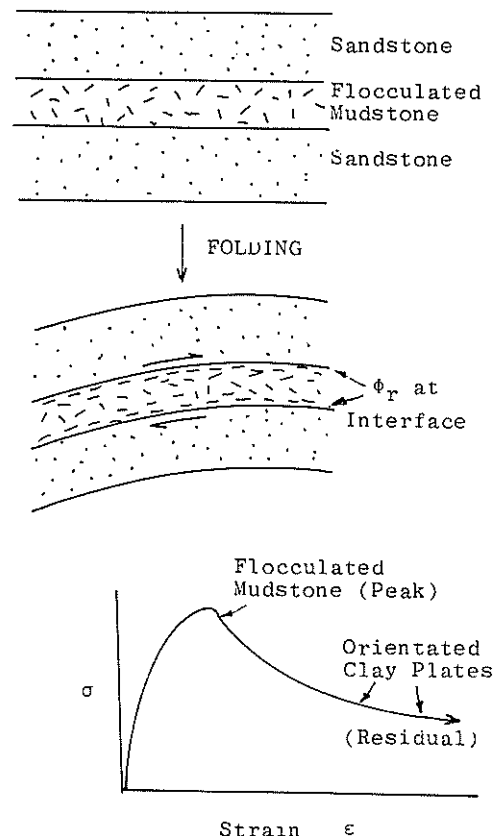


Fig. 1 Folding of a sedimentary sequence to produce residual strength at the argillaceous interfaces.

and for flexure. It might therefore appear redundant to labour the point. However, it has been the writer's experience that, on nearly every site where flexural slip seams have been encountered, they have either been missed during the investigations, or their origin has not been recognised - occasionally even actively disbelieved by engineering geologists.

Case histories are given below to illustrate this point. These have been chosen to include both sites where the problem was identified at an early stage and also sites where the problem was not recognised.

2 CASE HISTORIES - DAMS

2.1 The Hazard Recognised

The first detailed description of the significance of flexural slip seams in sedimentary rocks arose through investigations at Mangla Dam, (6). Here, alternations of clay shales and conglomerates had been moderately folded to produce complex shear patterns which showed a preferential association with the more clayey horizons. Within the shear arrays, flat polished and continuous surfaces were mapped; these were at residual strength.

Soon after Mangla, construction began on a 30 m high concrete dam forming part of the Muda Project, Malaysia; consultants were Sir William Halcrow and Partners. Initial drilling revealed mainly quartzites with mudstone partings, the series forming a dip slope on the right bank of the dam site. No unusual features were reported from the drill cores.

Prior to visiting the site in 1965, the writer identified on air photos what appeared to be a large dip slope slide on the same right bank. It seemed reasonable to assume that sliding had occurred on a mudstone bed and, further, that the mudstone might well have been weakened by flexural slip. Initial excavations for the dam confirmed this view. The mudstone was found to be sheared along its contacts with the quartzite although, elsewhere, it could have been described as a reasonably sound rock. It was, of course, the sound rock which had been retained in the drill cores.

As the strike of the beds approximated to the direction of the dam thrust, the sheared horizons in the mudstone posed a potential hazard to dam stability. A program of testing, with multistage in situ shear tests and complimentary laboratory tests was set up. Residual strengths with $\phi = 18^\circ$ were obtained, (7). As a result of these findings, the dam was anchored by high tensile steel cables which are still functioning satisfactorily today, Figure 2. Detailed descriptions of the geology and anchor design are given in (8).

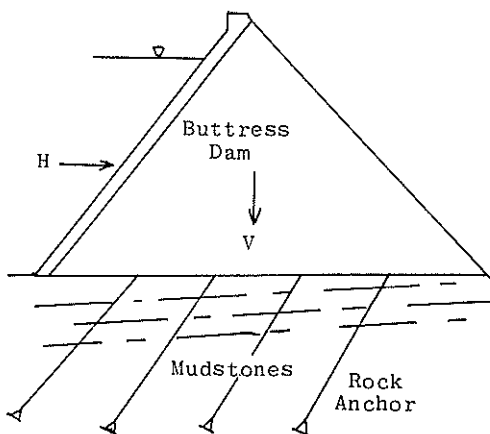


Fig. 2 Muda Dam, a 30 m high concrete buttress dam was founded on a quartzite-mudstone series. As a result of folding, the mudstone interfaces exhibited residual strengths, necessitating foundation improvement in the form of cable anchorages.

A similar situation to Muda has been described for Meadowbank Dam, Tasmania, (9). Here, in situ tests gave ϕ values around twenty degrees along the argillaceous bedding.

Flexural slip seams in almost swarm-like proportions occurred at Sugarloaf Dam, Victoria, (10), although their orientations were not critical to dam stability.

The above discussion was confined to sedimentary rocks. Flexural slip, or foliation, shears are also common in metamorphic rocks and a good account of them can be found in references (11) and (12). One case history is described below.

Kotmale Dam is a 90 m high concrete faced rockfill dam, constructed as part of the Mahaweli Development in Sri Lanka, in the early eighties. As at Muda, the consultants were Sir William Halcrow & Partners.

The rocks of the Kotmale area are hard Pre Cambrian gneisses with interbedded marbles known locally as limestones. The series is strongly foliated and has been moderately folded in Mesozoic times to produce a downstream dip of sixteen to twenty degrees at the dam site, with a component into the left bank. A typical dam section on the foundation is shown in Figure 3.

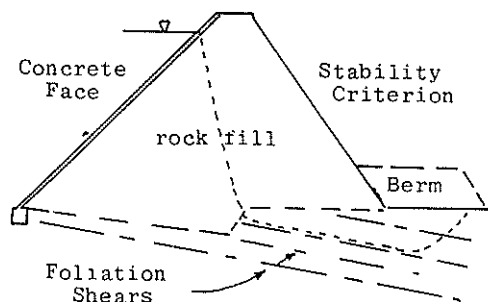


Fig. 3 Kotmale Dam, showing the foliation dip at the dam site. Six or seven major foliation shears were encountered in each abutment, traceable over tens to hundreds of metres.

Nothing unusual had been revealed by several drilling programs prior to construction. However, early excavation for a diversion tunnel revealed a band of highly weathered material in the sound rock, which contained a continuous, polished, surface parallel to the foliation. About this stage, doubts were expressed by client representatives as to the true origin of this and other similar features. Opinions were proffered that the polished surfaces were superficial features. Their continued existence at depth, in the diversion and other tunnels, generally dispelled this view. In any event, striations on the mirror-like surfaces showed movement had been in a direction at right angles to the dip, which ruled out gravity mechanisms. Displaced vertical dykes in the rocks gave direct evidence of the amounts of movement, measurable in tens of centimetres.

Multistage in situ shear tests were undertaken on the seams, together with a comprehensive laboratory program. Minimum strengths of $\phi = 12^\circ$ were obtained on first shearing of laboratory specimens. In situ tests gave a corresponding first shear value of $\phi = 15^\circ$, in the direction of dam thrust. There was little or no drop in strength on repeated shearing.

During later excavations on site, blocks of fresh rock, ten metres or more in plan dimension, slid down dip on inclinations as low as sixteen degrees. The majority of these were initiated by blasting, but the continued movement of the blocks confirmed that the value of the angle of shearing resistance, for very large areas, do not exceed that obtained for in situ tests by any significant amount.

It is to be remembered that these very low strength values occurred in otherwise hard rock. To neglect such dramatic planes of weakness would be to court disaster.

2.2 The Hazard as a Late Manifestation

At Maroon Dam, in Queensland, the whole right abutment of the dam site moved out abruptly a distance of some tens of centimetres during the excavation of a bottom outlet channel. The base of the movement was located on a subhorizontal plane which was highly polished. Tests on this showed a shear strength at residual, with $\phi = 13^\circ$, (5). The geological series was quite gently folded in the area. No evidence of any weak or sheared seams had been recorded during the drilling program and the original dam design had to be modified.

The writer was briefly involved in 1988 in the site for a very large concrete dam in south west China. The rock type was similar to Kotmale, above: gneiss with a strong foliation which gradually steepened from downstream to upstream. The formation had been mapped as being crossed by a number of translational faults, each identified by a wide zone of weathering. In each, distinct and slickensided seams were present. It was pointed out by the writer that the striations on these seams ran vertically down dip, rather than horizontally, as might be expected if shearing was through the tear faults. More, the faults in all cases neatly paralleled the changing foliation dip. The "faults" were, in fact, flexural slip seams, highlighted by broad weathering zones, at as Kotmale.

Malpasset Dam, a concrete arch dam founded on phyllites, failed in 1959. A full description of the disaster is given in (13), but some of the essential facts can be enumerated as follows:-

i) An enormous wedge of rock underlying the left abutment disappeared in the failure. The wedge was bounded on the downstream side by a fault, on the upstream side by a foliation plane, Figure 4.

ii) A stability analysis of the section in Figure 4 a, during design, gave an adequate Factor of Safety.

iii) Measurements showed that initial deformations occurred parallel to the left abutment of the arch.

iv) Sections of the dam were later found with foundation rock adhering to the concrete, indicating that failure along the concrete-rock interface was unlikely.

If we take a three dimensional view of the left abutment, Figure 4 b, we can see that both the line of the fault and the foliation strike lie subparallel to the abutment thrust. This situation produces a wedge of rock bounded on both sides by planes of weakness; this was the wedge which disappeared. The resistance to the dam's thrust along this wedge is provided only by the strength of the two discontinuities: a fault zone and a foliation

shear. The strengths along both would be unlikely to exceed and angle of shearing resistance of about twenty degrees.

A simple analysis of the stability of this wedge, (14), makes such a failure mechanism logical, without the need to call on any excessive uplift pressures.

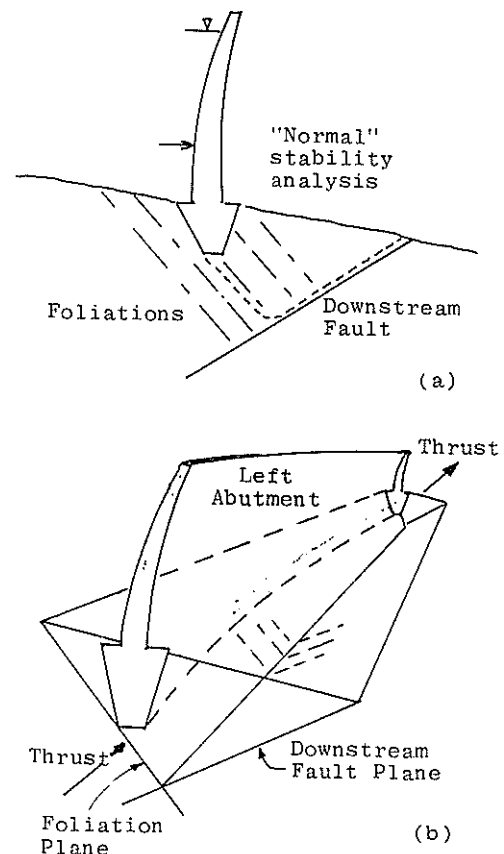


Fig. 4 Malpasset Dam, showing sections a) normal to the axis, which gave an adequate Fof S, and b) along the left abutment alignment, where weak discontinuities bounded the wedge of rock which was removed during the failure.

The St Francis Dam, in California, slid downstream in 1926. The foundation rocks were a series of conglomerates and shales, similar to those at Mangla and failure occurred in the weaker members. At the time, failure was put down to high pore pressures but, with the benefit of hindsight and present day knowledge, we might reasonably assume that flexural slip seams were present and had a large bearing on the failure.

3 CASE HISTORIES - INSTABILITY

Perhaps the most spectacular slope failure in recent times has been that at Mt Toc, above the Vaiont Reservoir. Here, a series of folded Alpine sediments dipped towards the valley, Figure 5. Failure took place in the Malm: thinly bedded limestones and marls. An analysis by Skempton (15) indicated a ϕ value of the order of 16° was required, for the relevant ground water and reservoir levels.

This slide thus has all the attributes of an example of failure along bedding plane shears which are the result of flexural slip. It is apparent from the

literature, however, that many engineering geologists are unwilling to accept this explanation and tend to seek corroboration, by analysis, of laboratory strength values obtained from intact rock samples.

Certain open cut coal mines in Central Queensland have suffered slips with basal failures on variously dipping bands of "clay" within the overburden siltstones. The clay is of similar mineralogy to the ambient rock and does not appear to represent a sedimentary hiatus. The clay also contains a sheared horizon which, to the author's knowledge, has received the attention of very little testing; one direct shear test indicated an angle of shearing resistance of twelve degrees.

This clay band, in otherwise sound siltstone, is an obvious flexural slip candidate, yet there again appears to be an unwillingness among mining geotechnical personnel to use this fact.

In Brisbane city, a moderately hard Mesozoic tuff overlies Palaeozoic phyllite unconformably. The phyllite surface exhibits paleoweathering, while folding of the combined formations has produced continuous slickensided shears along this weathered interface zone. In this case, flexural slip occurs on an interface separating formations with an age difference of millions of years. The effect of this interface on stability has been discussed elsewhere, (16).

Limestone poses a special case in flexure. The residual angle of friction for limestone appears to be not much less than the friction value along joints: perhaps thirty five compared to thirty seven or eight degrees. When a massive limestone is folded, adjustment by flexural slip causes a grinding and pulverisation of the rock along the slip plane(s). This makes the horizon more susceptible to solution, so that the flexural slip planes become highlighted by a microkarsticity.

The writer was involved in the excavation of an 80 m. high spillway cutting in massive limestones, in S.W. China. The dip was downstream, with a component out of the valley side. Four or five bedding planes had been mapped as daylighting in the cut; these were characterised by solution planes partly filled with red clay gouge. Rock to rock contact was of the order of 50 - 60 %. The designers had received advice that these clay-filled planes would die out at depth, which advice is believed to indicate a misunderstanding of the origin of the features. In any event, the gouge filled planes were exposed in a diversion tunnel, well below the base of the spillway. The wedges formed by these planes had to be supported by a series of anchors.

4 DISCUSSION

In the foregoing case histories, some emphasis has been placed on the need to differentiate between flexural slip planes and planes of weakness resulting from other causes. This differentiation is not merely of academic interest, and two examples should suffice to illustrate this.

Consider a situation of potential seismic risk at a dam site. This was a concern at one site mentioned above, where an active fault was known in the region, and the mapped "translational faults" at the site ran subparallel to this. Hence the "translational faults" could have been sympathetic features, themselves capable of activity - either natural or reservoir induced.

Recognising the origin of these features, not as translational faults, but as flexural slip planes, the result of Mesozoic folding, was a major factor

in allaying concern about their future seismic behaviour.

The case of the slide into the Vaiont Reservoir is one where resistance to the concept of flexural slip is still evident in recently published papers on the topic.

If one does not understand the origin of features which have initiated past slides, one is liable to make errors of judgement when encountering similar phenomena in the future.

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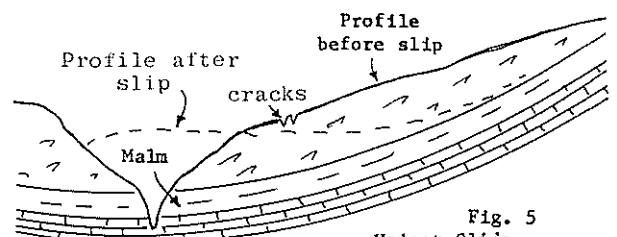


Fig. 5
Vaiont Slide