The Value of Field Studies in Earth Dam Design

La Valeur des études de chantier dans le calcul des barrages en terre

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SUMMARY

The design of earth dams is gradually evolving from rule of thumb to a more scientific basis; theories are proliferating and the use of soil tests is commonplace. The author believes that orderly progress is impossible unless the results of field measurements are also applied to methods of design. During the construction of a number of earth dams with which the author has been associated, observations of pore pressure have been made together with measurements of shear parameters and other properties of samples extracted from the fill. These values have been used to check the stability of the dams during and after construction (e.g. during drawdown). The paper describes the techniques used and the way in which forecasts have been made from these observations for the design of subsequent dams.

SOMMAIRE

Les projets de barrage en terre évoluent graduellement de la méthode empirique à l'application de formules scientifiques nouvelles. Les théories se multiplient et les essais du sol sont communs et fréquents. L'auteur soutient qu'une progression méthodique n'est possible que si les résultats obtenus sont appliqués aux nouveaux calculs. Durant la construction d'un certain nombre de projets auxquels l'auteur a été associé, des observations sur la pression interstitielle et la résistance au cisaillement furent notées, de même que les propriétés des échantillons extraits du remblayage. Ces notes servirent à vérifier la stabilité des barrages durant et après leur construction (e.g. durant l'affaisement). Le rapport décrit les techniques en usage et les prévisions faites durant les projets subséquents grâce à ces notes.

ALTHOUGH THE AUTHOR had been vaguely aware of the work of the U.S.B.R. in observing pore water pressure in earth dams (Walker and Daehn, 1948) and rather more aware of the difficulties experienced at Muirhead (Banks, 1948), it was not until the construction of the Usk dam in South Wales (1950–56) that he became personally involved with these malignant forces and fully appreciated their great importance to the dam builder.

It has been standard practice on all the dams with which the author has since been concerned to measure settlements and pore pressures and to take samples of fill to determine shear parameters, compressibility, and permeability of the material as placed. These measurements are then used to check the design assumptions. In some cases, this has led to modifications being made to the dam cross-section.

USK DAM

The Usk dam was built between 1951 and 1955, with shoulders of the local Pleistocene boulder clay of glacial origin and a core of puddled alluvial clay (Sheppard and Aylen, 1957). The area is one of comparatively high rainfall (*c.* 55 inches per annum); not only were conditions

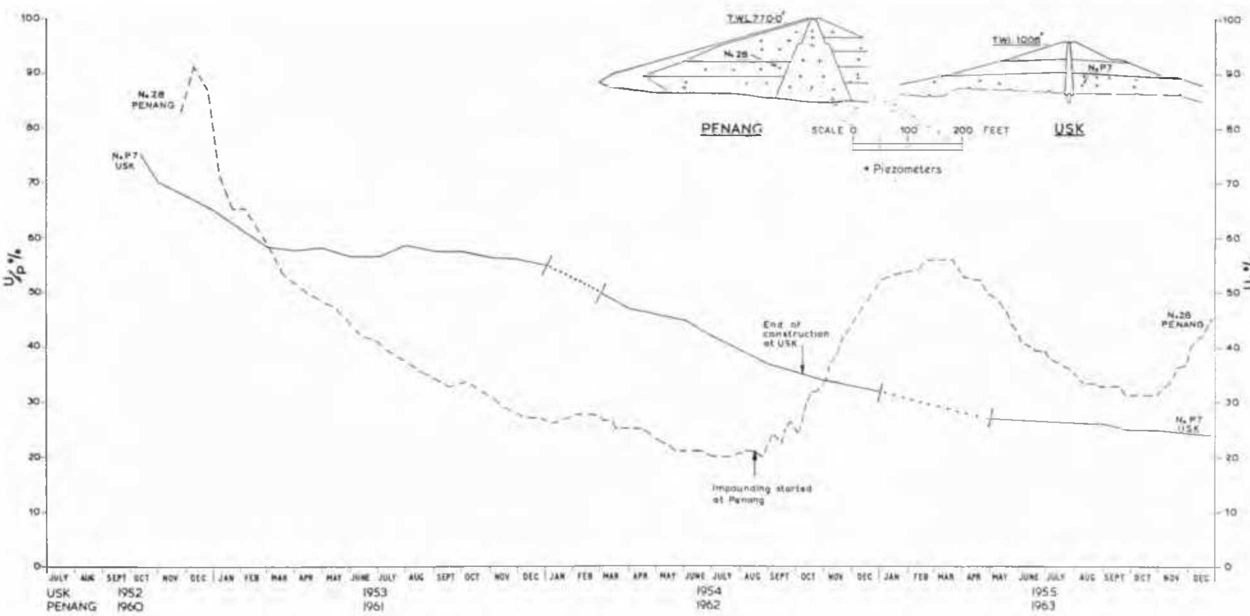


FIG. 1. Dissipation of pore water pressures at typical points in the Usk and Penang dams.

during construction rather wet but, in the borrow area, the available material had an average water content of 11 per cent compared with a Proctor optimum of about 10 per cent. In the first season, the fill was placed at a water content rather higher than that in the borrow pit but in subsequent seasons, the contractor succeeded in improving placing conditions so that the water content was little different from the borrow pit value and therefore about one point above the optimum.

Piezometers and standpipes were installed at various times during the construction period and at an early stage it became clear that high pore pressures were being generated within the fill. Indeed, on one occasion, the piezometric level within a standpipe rose above bank level. It was decided to install horizontal drainage blankets at 40-foot vertical intervals in the dam to ensure that the pore pressures would dissipate at a rate which would enable construction of the embankment to proceed and complete the work within a reasonable time.

Consideration of the pore pressures in Fig. 1 show that, after reaching a maximum value, they began to dissipate until impounding began in October, 1954. The downstream pore pressures were unaffected by this but when the reservoir level reached the upstream piezometric levels, they responded and followed the rising water level fairly closely. After completion of construction, it was intended to continue observing the behaviour of the piezometers with fluctuating reservoir levels. By an unfortunate coincidence, the installation was damaged by frost just as the reservoir was drawn down for the first time; for the following two seasons, the results were inconclusive. It was not until 1959 that it was clear that the pore pressures rose and fell with variations in the reservoir level (Gilbert, 1962).

PENANG DAM

The Ayer Itam, Penang, earth dam, 170 feet high, is in an area of intense tropical weathering and high rainfall. During the construction period (1960 to 1962), the measured rainfall averaged 102 inches per annum. It was anticipated from the experience at Usk outlined above, that high construction pore pressures would be developed. This proved to be correct although some anomalies were detected in the readings. These were subsequently explained as the effects of pore air pressure on course ceramic piezometer tips of low air entry value installed in a partly saturated fill (Little, 1964).

For design purposes it was assumed that the contractor would raise the embankment by an average rate of 9 feet per month (compared with 4 feet per month at Usk). Based on test results and fortified by the Usk experience, it was concluded that the initial r_u value (ratio of pore pressure to total vertical stress) would not exceed 85 per cent. From experience at Usk it was concluded that the pore pressures would dissipate in accordance with Terzaghi's consolidation law; hence it was possible to predict with some confidence the pattern of pore pressure developed during construction. It appeared that horizontal drainage blankets would be essential here, as at Usk, to prevent the development of excessive construction pore pressures. Subsequent experience justified these conclusions. Fig. 1 shows the development of pore pressure at a typical piezometer compared with a similar result for Usk.

At the time of designing the Ayer Itam dam, it was not known for certain what would be the effect of variation in reservoir level on a dam already experiencing construction pore pressures. Although theoretical considerations suggested that the effect of rising external water level would not be *additional* to construction pore pressures, this had not been conclusively proved by direct measurement.*

At Ayer Itam, conditions were more favourable for observation than at Usk and Fig. 2 shows in a striking manner how an upstream piezometer responded to variation in reservoir level. As soon as the external water level rose above the piezometric level corresponding to construction pore pressure, the piezometer reading responded to the external stimulus. When the external level fell, the dissipation process was resumed at the same rate as before.

It has already been mentioned that samples from the fill as placed are taken and tested as a matter of routine. This was done at Ayer Itam but interpretation of the results gave rise to some concern, particularly over the stability of the upper part of the downstream shoulder of the dam. It was difficult to decide, from the Mohr circles obtained from consolidated drained triaxial tests, what value of c' was reasonable (Fig. 3a). Unfortunately, this had an important effect on the factor of safety as determined from circular arc stability analyses (Fig. 3b). It will be seen that the factor of safety, $F = 1.50$ for $c' = 200$ lb/sq.ft. (circle centre B_0), drops to the undesirably low value of $F = 1.15$ for $c' = 100$ lb/sq.ft. (circle centre A_0) (Little, 1962). In fact, although the recorded pore pressure under the full height of bank was 66 per cent of the overburden, no slipping, either deep-seated or on the surface,

*Although subsequently established for the Usk dam (see above).

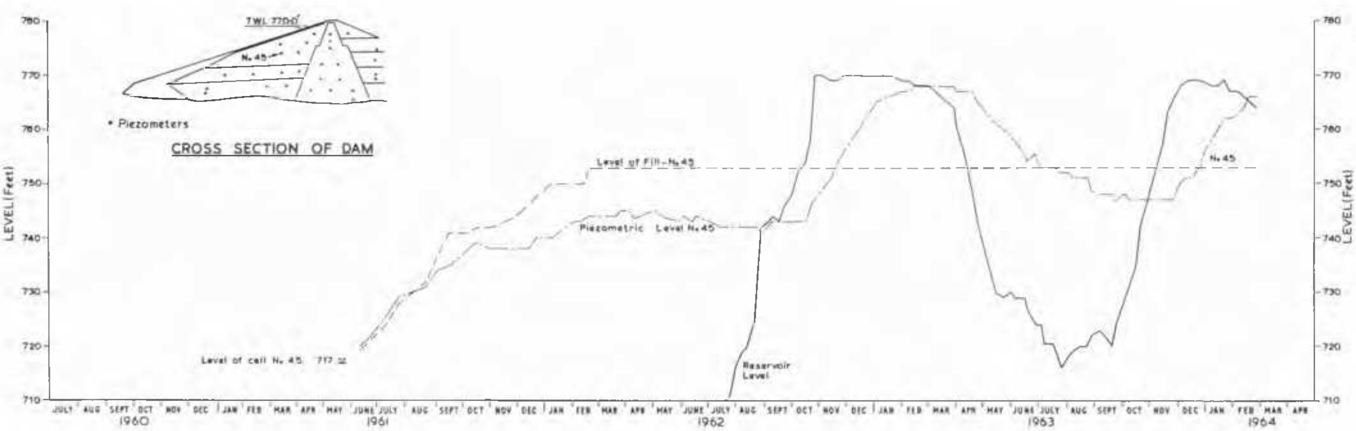
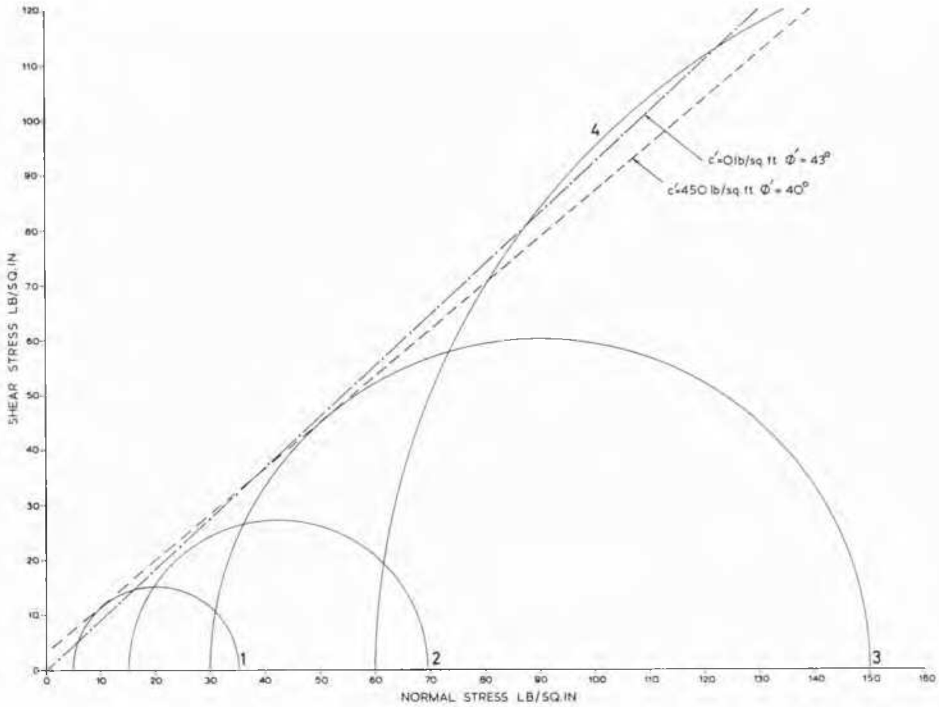


FIG. 2. Penang dam: response of upstream piezometric level to reservoir level.



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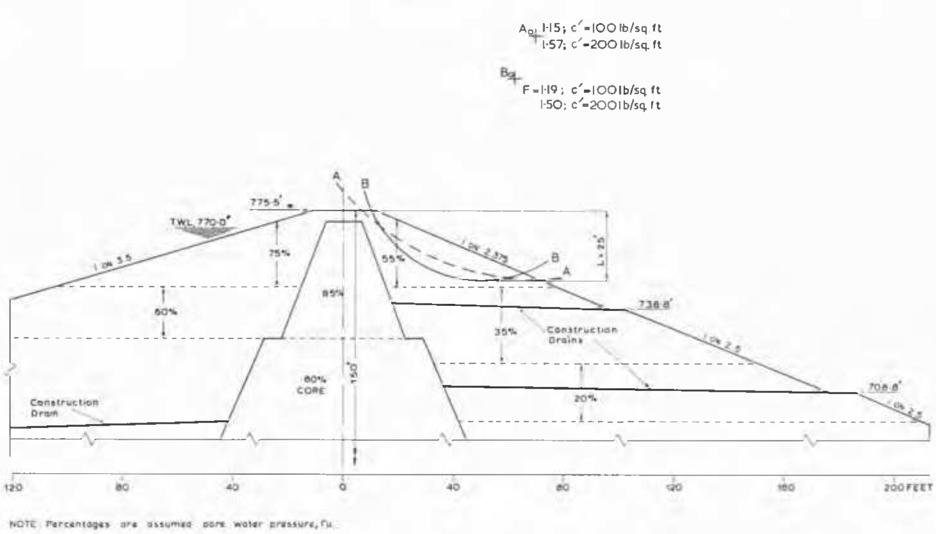

B

FIG. 3. Penang dam. A, typical consolidated drained triaxial test result. B, stability of downstream shoulder.

took place. This was in part undoubtedly due to a reduction in pore pressure towards the surface of the slope which was not taken into account in the calculations.

SHEK PIK

The Shek Pik dam was constructed on Lan Tao Island, part of the New Territories in the Crown Colony of Hong Kong (1962, 1963). It was known that the rock at Hong Kong is, in general, granite, decomposed at the surface by intense weathering. Although geological investigations for the tunnel and cut-off had established that the rock was volcanic (rhyolite) and not igneous (granite), it was assumed (incorrectly, as it transpired) that the weathered decomposed bedrock when used as fill would behave in a similar manner to the fill at Penang. A preliminary investigation showed a large deposit of coarse alluvium upstream of the dam site and considerable quantities of weathered decomposed rock in the hills around the reservoir. A cross-section was therefore developed using the alluvium to form an upstream pervious shell with a core and downstream shoulder of the decomposed rock (Fig 4a). The dam was designed on the assumption of high pore pressures in the core, with drainage blankets (and consequently lower pore pressures) in the downstream shoulder. Various assumptions were made about the development of pore pressure in the upstream shell but as excavation of the alluvium progressed it became apparent that it would be necessary to make allowance for full drawdown pore pressures.

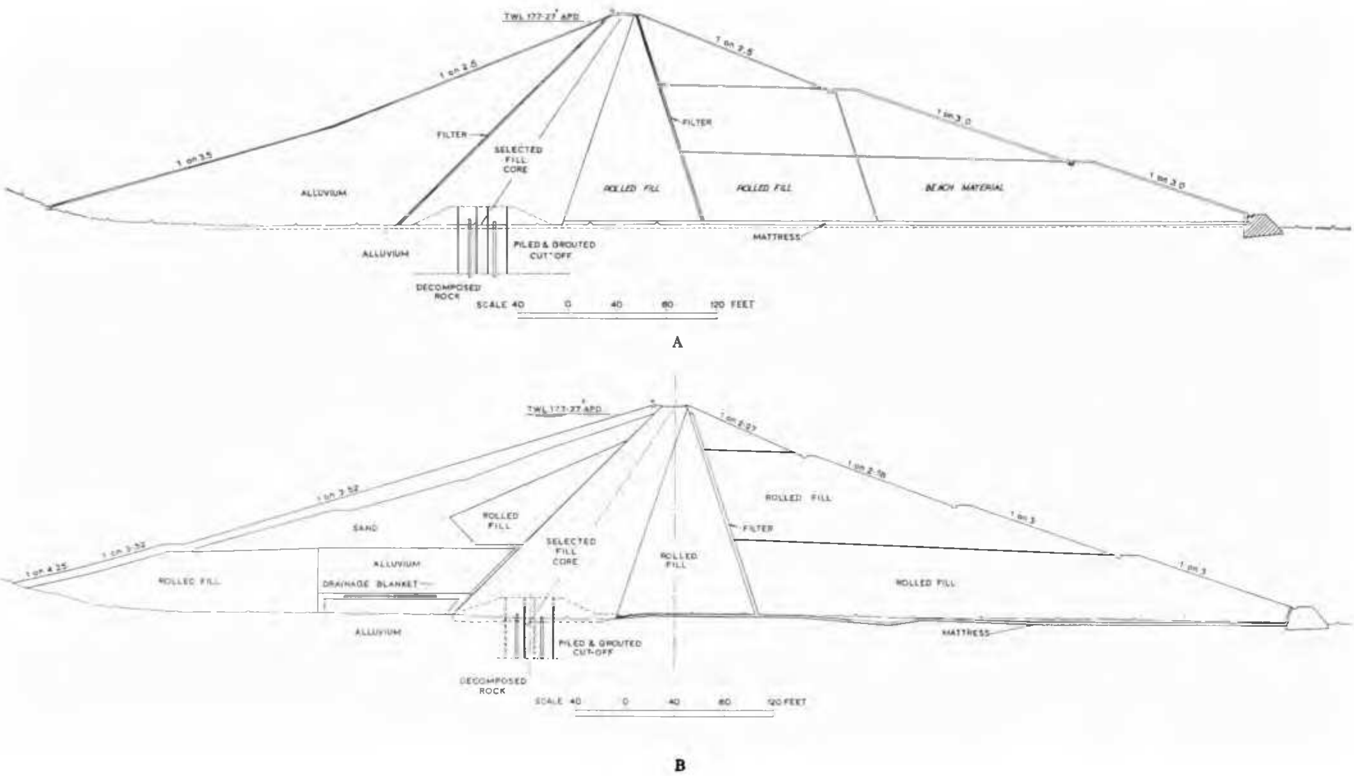

FIG. 4. Shek Pik dam. A, original design. B, final design.

Early experience in placing fill reinforced by the more detailed investigations of borrow areas which became possible once the contractor was on the site revealed deficiencies in available materials. Accordingly, fairly extensive redesign had to be undertaken and the final cross-section was as shown in Fig. 4b. During construction of the dam, it was apparent that the decomposed bedrock had very different properties from that at Penang and this was confirmed by the low pore pressures which were measured. The appearance of the fill at Shek Pik which resembled a dry sandy silt was unlike the Ayer Itam fill which was rather sticky and clayey. During construction, extensive cracking was detected in the core; this has been reported on more fully elsewhere (Little and Beavan, 1963) and an extensive remedial programme undertaken.

NEGATIVE PORE PRESSURES

Two small dams (*c.* 30 feet high) were constructed in the 1955–56 seasons in southern England of fills derived from overconsolidated clay deposits. Hanningfield No. 2 dam, Essex, was of London clay, and Foxcote, Buckingham, was of a stiff-fissured grey clay, probably redeposited Cretaceous (Gault) clay.

Measurements of soil properties showed that the embankments would have high initial strengths, but little was known about the long-term effects of "softening" on performance. Accordingly, the method of effective stress analysis was not used and the banks were designed on a total stress basis using the concept of softening in stiff-fissured clays as developed by Skempton (1948). A value of c_u = 400 lb/sq.ft. was chosen for both sites as representing the most likely value of the ultimate undrained strength of the material. At the same time, it was deemed prudent to install piezometers in the embankments, not only to secure advance warning of the development of any dangerous condition but also to investigate the behaviour of the materials during and after construction.

At both sites, small negative pore pressures were measured initially (Fig. 5). Even at the time, because of the need for frequent de-airing, it was realized that air was entering the piezometers and affecting the readings (Little and Vail, 1960) but it now seems probable that the recorded pore

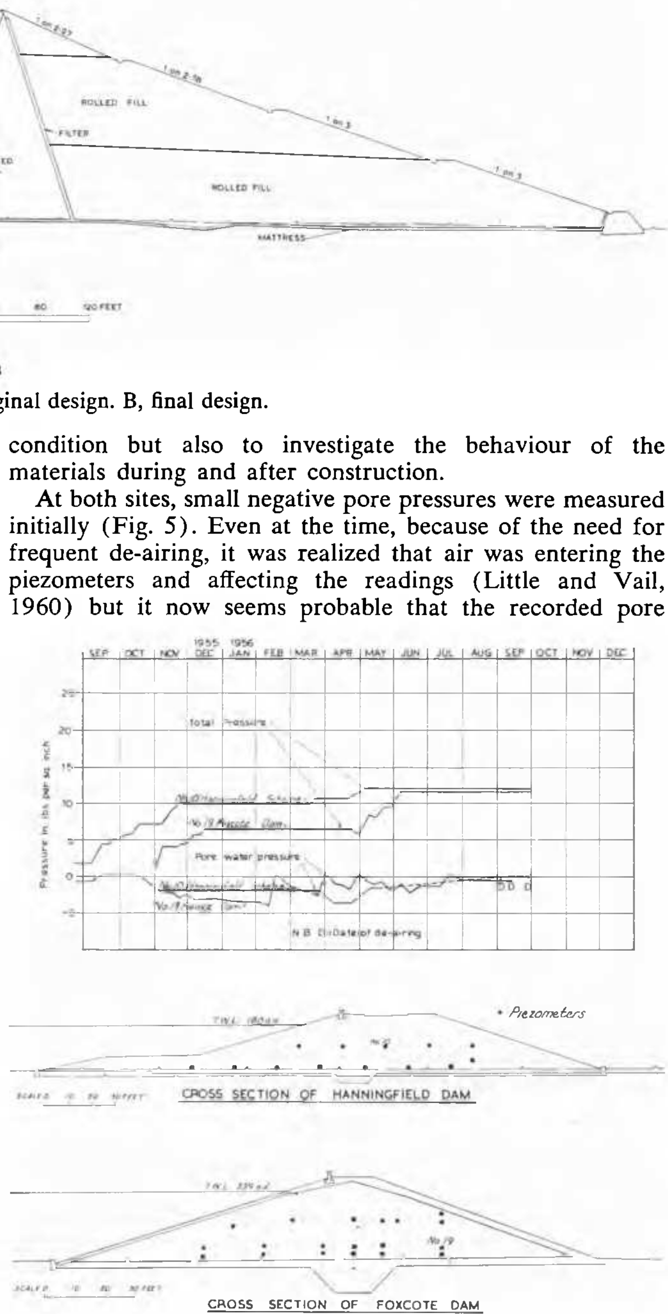

FIG. 5. Pore water pressure measurements at Hanningfield and Foxcote dams.

pressures would have been much more strongly negative had high air entry value ceramic tips been available (Bishop, Kennard, and Vaughan, 1964). Nevertheless, these readings did demonstrate that negative pore pressures, as anticipated from theory and from laboratory tests, were developed in the prototypes. This gave confidence for the use in future designs of allowance for the development of negative pore pressures. Not only would the development of negative pore pressures increase the stability of a dam during construction but it would also permit higher rates of construction to be used without generating high construction pore pressures.

The core of Mangla dam (*c.* 330 feet high) is being constructed of very heavily overconsolidated Siwalik clay in which negative pore pressures were expected to develop. At the time of writing (April, 1964) no field data are available, but laboratory tests on saturated specimens of the compacted clay have shown that negative pressures develop at low applied stresses and that even at high stresses, the pore-pressure response is greatly reduced. The curve of Fig. 6 has been developed from these tests and used in design. Field measurements using piezometers with tips of high air entry value ceramic will determine the pore-pressure responses during and after construction and so enable the performance of the dam to be correlated with the design assumptions.

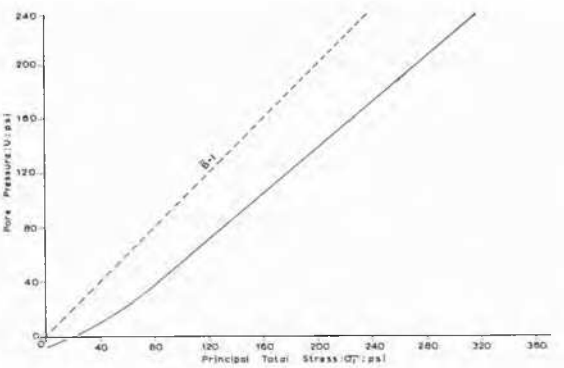

FIG. 6. Mangla dam: relationship between construction pore water pressure and principal total stress used in design.

Since the design of Mangla was completed, further negative pore-pressure readings have been recorded using high air entry ceramic tips at Diddington, Huntingdonshire. The fill is a heavily overconsolidated clay and typical readings confirm that strongly negative values are developed.

Theory suggests and observations confirm that negative pore pressures are destroyed by the absorption of water, a process that presumably continues until an equilibrium condition is reached. Therefore the concept is applicable only to short-term conditions like construction. It is unlikely that sufficient confidence would have been felt to use the negative pore-pressure concept in the design of such an important structure as Mangla dam unless it had first been proved in the field by measurements such as those at Hanningfield, Foxcote, and Diddington.

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