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are taken normal to the direction of strike of the defect planes that are responsible for the geometry of each slope. Also, by using stability methods much as proposed by Petzny (1964) with suitable assumptions regarding characteristics of the rock mass, similar exponential correlations are obtained by including water pressure effects. The relevance of this method of analysis in the prediction of the *in-situ* strength and deformation characteristics of rock masses will be discussed in a paper to be published in the near future.

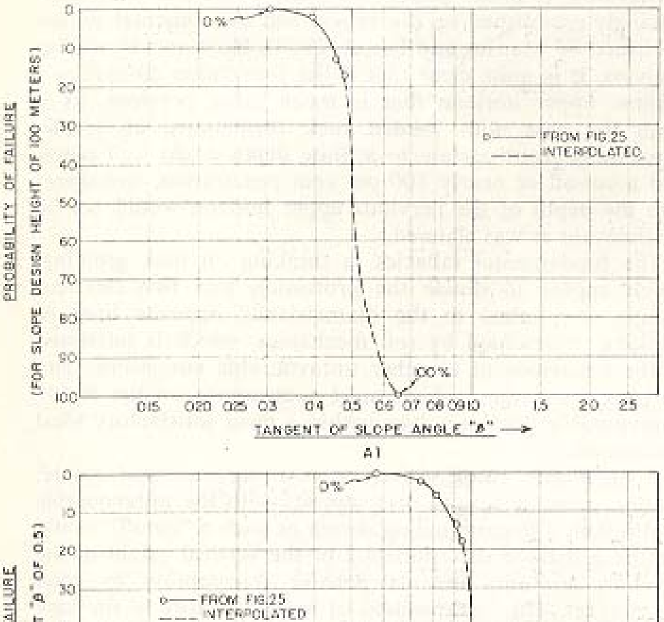

FIG. 26. Probability of failure: (*a*) *versus* tangent of slope angle for slope design height of 100 m, (*b*) *versus* height of slope for slope design tangent of 0.5.

From Fig. 25, a procedure for a "probability of failure" analysis for the slopes can be postulated. Conceivably, it can be reasoned that two lines lying parallel to the median at the upper and lower limits of all the points, such as shown on Fig. 25, represent the 100 per cent and 0 per cent probability of failure curves for these slopes, if the period of time for the slope stability prediction is not longer than that of the diagram (14 years). By joining groups of points representing failed slopes, with lines parallel to the median (such as the 3.3 per cent probability of failure line shown on Fig. 25), a probability of failure curve can be obtained for each design slope height and angle. Based on Fig. 25, curves for a design height of 100 m and tangent of slope of 0.50 (2 on 1) are shown on Figs. 26A and 26B respectively.

An approach such as that described, combined with a sound decision as to an acceptable design probability of failure as suggested by *Langejan (6/15)*, would allow for a more rational approach to slope design in engineering.

However, one very important factor has been neglected by Langejan as well as other writers on these subjects. This factor is time, as was brought to our attention by Mr. Feld in his lecture. Fig. 25 shows that within what could be considered the normal life span of an engineering project, five slopes have failed, two on a number of occasions. These failed slopes probably had a factor of safety of one, or somewhat higher. It is interesting to note that some of the stable slopes have greater heights or slope angles than the slopes that have failed. Apart from the variability of the conditions and characteristics of the materials within a given geologic formation in such a large area, these slopes can be probably grouped in that category which Terzaghi once called "held up by an act of God."

Based on the logical premise that all natural and man-made slopes have a probability of failure—the question being how long will they take to fail—the following conclusions can be stated. (1) The term "factor of safety" as used at present in slope stability problems is meaningless unless it is related to time parameters, and it can be a tranquilizer with bad after-effects if it is used only on the basis of strength parameters. Although it is a more rational approach, the use of "probability of failure" methods, such as that proposed by Langejan are equally rational. (2) Factor of safety and probability of failure cannot be related to one another, unless both are based on the same time parameters.

Some attempts at a theoretical approach to time effects have already been made. Scheidegger (1961) presents mathematical models for the evolution of slopes with time. Unfortunately, these models are based on gradual changes closer to a geologic time scale; some of the models presented could, however, be treated mathematically to include the more rapid failures encountered in engineering problems. *Saito (6/24)* and Skempton, in his discussion, in this Session, present interesting approaches to this type of analysis. These efforts are essential. It is hoped that the results of the endeavours to relate time to "factor of safety" and to "probability of failure" anaylses will be available at the time of our next conference.

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V. F. DE MELLO (Brazil)

The authors of paper *(6/5) (Bolognesi, et al.)* added another case history to the turmoil of discussion on the efficacy of curtain grouting for rock foundations of earth dams, but once again the data that might permit a complete and impartial judgment are lamentably lacking. And although the precaution of qualifying the attack as pertaining to "indiscriminate grouting" is taken, the predisposition to criticize appears rather transparent.

Since everyone will agree wholeheartedly with the closing statement that "grout cut-offs should only be used where a throughly competent and detailed analysis shows that they will be efficient for the purpose for which they are envisaged," it seems to me that in all fairness one should begin somewhat further back than the authors deemed necessary, in fact with a complete quantitative description of the jointed pervious rock substratum, as a prerequisite to any appreciation of the foundation treatments applicable or required.

It is, therefore, most regrettable that the paper cannot be discussed in the light of a case history, since no data were furnished, beyond the description that the local rock is a gneiss subjected to folding and faulting (Grandi, *et al.*, 1961) and that Lugeon water tests were performed during the execution of the grout cut-off, and since their results were not introduced in the analysis. Nor were they presented because of some presumed question as to their accuracy.

As regards the water pressure test and its interpretation, I fail to see in what respect the very nature of the tests should compare so unfavourably in accuracy with piezometer readings. One very important consideration that has forced itself upon me in the course of continued investigation on the subject since publication of the paper in the First Panamerican Conference, Mexico, 1959, is that the water pressure test should be allowed to probe the extent and nature of the open points in the rock mass, in order to permit satisfactory interpretation of water losses and grout takes. Thus, whereas for quantitative correlations I had earlier proposed the use of water loss coefficients obtained from routine tests conducted on 10-ft lengths of the drill hole, it subsequently proved obvious that such average values could not possibly bear a very direct relationship to problems of seepage through rocks except in the case of closely and uniformly jointed masses wherein a 10-ft length became satisfactorily representative. In many rocks, including particularly our local gneisses, granites, diabases, and basalts, open joints are very often few and far apart, but widely open. A simple way to probe their nature in connection with water loss coefficients is to use top and bottom packers and to reduce the distance between them in repeated tests while continuing to straddle the open joint. It has thus become our standard procedure to require that wherever the routine test gives water loss coefficients higher than 1 liter/min/m atmosphere, and the rock type warrants it, the nature of localized open joints should be carefully probed by a pinching-in procedure reducing the distance between packers. In some cases we have detected single cracks responsible for the entire flow within the 10-ft length, and have computed water loss coefficients of twenty to thirty times the original average value. Advancing beyond present practical limitations it is not difficult to conclude that a tested length of 10 cm may comprise but a single open joint less than 1 cm wide, and therefore a truly representative water loss coefficient might often be 100 to 1000 times greater than the original average value.

Reverting to an analysis of the grout curtain discussed by the authors, it may be concluded that (1) no special rock horizons or conditions were observed, investigated, or meant to be treated by the grout curtain used, a situation which surely merits the description of indiscriminate grouting; (2) the authors interpret the bedrock as a pervious continuum, isotropic and semi-infinite, with Darcy's law valid; (3) the effective grout curtain is assumed to be a totally impervious plane; (4) the grouting treatment was expected to produce a drop in average uplift pressure immediately downstream from the curtain, and its eventual effectiveness was to be reflected in piezometer measurements, wherein the term piezometer is attributed to drainage holes 10 cm in diam and 22 m deep, geometrically distributed along the longitudinal and transverse cross-sections; (5) it is stated that limitation of the depth of the permeable foundation would change the distribution of the equipotentials below the foundation very little.

To begin with, if the foundation may aptly be considered a pervious continuum down to infinite depth, it is rather unnecessary to prove that a partial cutoff, even if absolutely impervious, is quite ineffective. Such proof has been convincingly established by theoretical and experimental studies published by Mansur and Perret (1948). However, by similar analyses, it is quite clear that if the foundation comprises a shallow upper horizon that is much more pervious, as is often the case with jointed rock formations, an ideally impervious grout curtain to a finite depth could well represent a cut-off of nearly 100 per cent penetration, and therefore the depth of the pervious upper horizon would not be as irrelevant as was claimed.

The fundamental fallacies in thinking on rock grouting, which appear to divide the profession into two clear-cut groups, are linked to the diametrically opposite lines of thinking represented by soil mechanics, which is interested in the behaviour of a rather unfavourable continuum, and by rock mechanics, which must concentrate on the highly unfavourable discontinuities within a most satisfactory ideal continuum.

A sheet-pile cutoff driven into a pervious soil would, ideally, create a desired discontinuity with the unfavourable continuum; a discriminating design of such a "cutoff" would require a definite determination of the vertical extent of the pervious stratum, and its positive interception by total penetration. The transposition of such a picture to the case of curtain grouting in fractured rock is clearly unwarranted. As is undisputably demonstrated by the effects of grouting on moduli of elasticity, the grout purports to seek out the discontinuities and to fill them to a degree; thus, with respect to water loss, a highly concentrated local flow is considerably decreased or even stopped by the grout filling.

Since the probabilities of the grout travel depend directly on the width and extent of the initial cracks, the reasoning behind a grout curtain must be that an ideal grouting programme should pick up the original discontinuities and treat them in direct proportion to their importance, thereby tending to achieve a continuum. Such a conception is diametrically opposite to that on which ideal sheet-pile cutoffs are based. Further, since discontinuities tend to be rather indiscriminate geometrically within the geologically established average patterns, a somewhat indiscriminate line grouting quite understandably has a much more tenable position as a sound engineering criterion than would at first sight appear to simplified mathematical theorizing. And, particularly if the effectiveness of a treatment of discontinuities is to be measured, whether by flow or by piezometer measurements, it stands to reason that the measuring device should not be installed in a geometrical pattern that presupposes reasoning on the continuum, but should be localized and specific to the discontinuity in question. A piezometer tip, 20 m long and 10 cm in diam, may indicate average uplift conditions of interest from a practical standpoint, but it would not be accepted for the detection of the nature of a flow net within a soil continuum; nor, *a fortiori*, can it reflect the eventual effectiveness of grouting in partly sealing a specific important discontinuity.

Finally, a word about the use envisaged for single- or multiple-line grout curtains and how their effectiveness may be verified. Two fundamental facts must be recognized, in absolute contradiction to concepts that seem to prevail in everything that has been written on the subject. Firstly, the best that grouting can do is to reduce the average effective permeability of the treated rock mass from tenfold to one-hundredfold; total imperviousness is sheer delusion. Secondly, the concept of a narrow curtain of constant width of treated rock is quite fallacious; grouting distances vary in direct proportion to the importance of the seams, being known to extend frequently to distances comparable to the bases of impervious cores of rockfill dams.

Curtain grouting treatments would thus fall under two classes of reasoning. Firstly, if the boundary conditions of a pervious horizon are well defined, a totally penetrating curtain treatment may be planned to reduce seepage losses. The effectiveness of such a treatment is principally reflected in flow measurements; and it must be conceded that there is ample evidence of the successful application of grouting for reducing flows. The obvious question which arises is the concomitant effect on uplift pressures, particularly since there is a widespread notion that all treatments of pervious foundations should aim at the control of uplift pressures, and since on first thought flows and pressures seem inexorably related. If we reason, however, that the nature of a flow net is principally related to boundary conditions and to relative permeabilities prevailing in different zones, it is not hard to comprehend that under a core of permeability of 10^{-8} cm/sec, if the entire horizon of foundation rock is changed from an effective permeability of 10^{-3} cm/sec to one of about 10^{-4} to 10^{-5} cm/sec, no measurable changes in uplift pressures are to be expected. Such a treatment should be questioned and justified on economic bases, considering the probable reduction in water losses. Multiple-line curtains should reduce effective permeabilities more than single-line curtains, although the width of the treated zone may not vary much.

Secondly, if no specific underseepage condition may be geometrically idealized, but the nature of the rock indicates important open seams erratically distributed, a single-line curtain of relatively indiscriminate grouting may well be desired. Whether or not concentrated preferential flows and pressures within the rock are felt to be of any consequence to the rock itself and to the dam fill depends very much on the rock and on the design cross-section. But, no theoretical reasoning based on flow nets is applicable, and average permeabilities and gradients give no inkling of the probabilities of occurrence of a localized condition disproportionately worse than the one assumed. The theoretical and actual behaviours of such grout curtains cannot reasonably be compared by drawing flow nets. The effectiveness of such indiscriminate grouting depends on the probabilities of the drill holes and grout picking up the important seams, and it can therefore only be assumed by measurements of changes of flows and pressures at such seams. Single-line curtains may well be as effective as multiple-line ones.

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A comprehensive report on field measurements performed at El Infiernillo Dam during the construction and first filling of the reservoir has been presented elsewhere (1965). Here, a few preliminary correlations are outlined. The dam was completed on the Balsas river in Mexico in December, 1963. On the plan (Fig. 27), the location of those instruments involved in this presentation is shown. The following instruments were selected: two cross-arm installations in the rock fill, one upstream (D-1) and the other downstream from the core (D-2); one inclinometer in the core (I-I) and another in the downstream rock fill (I–III); and three reference monuments, one at the crest (M 10) and the other two in the downstream berms (M 23 and M 30).

Fig. 28 contains some settlement data obtained by means of the cross-arms and inclinometers in the locations shown. Vertical displacements (Fig. 28, left) refer to changes in elevation from the installation of each reference point to the date at which the dam was topped off. Consequently, the last section of casing in the core had just been installed when these observations were made, so that there was practically no settlement of the top reference point. Since installations in the rock had been finished some time before, settlements

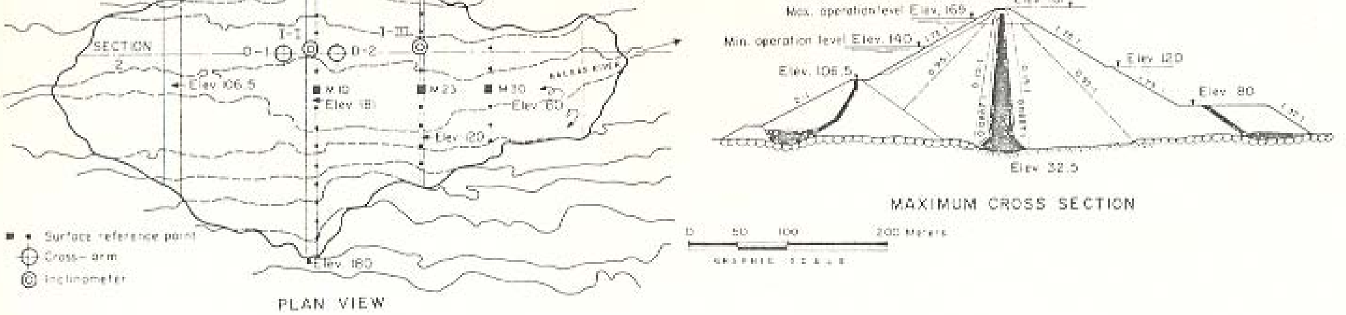

FIG. 27. El Infiernillo Dam.