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Practice, precedents, principles, problems, and prudence in embankment dam engineering

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SYNOPSIS. Practice and precedents are often quoted as supports for design decisions: this can be very wrong and dangerous unless case histories are analysed under tenable theoretical principles. However, even in the analysis of case histories we must be the devil's advocates in resisting the straightjacketing imposed by a given mental model against which an important unusual fact may be helpless. Examples are given of common fallacies. Some of the principal problems of design, materials selection, and construction specifications are shown to be formulated under intuitions that do not resist analysis. Examples of present most recognized problems are described. The place of statistics and determinism in design decisions are compared. The very fact that our theorization for quantification presupposes statistics of averages whereas catastrophic failures are events closer to extreme values, imposes a need for prudence in choice of design by physical model, such that a feared misbehavior be virtually excluded, in advance of any design computations.

1. INTRODUCTION

Practice and Precedents have been much lauded by the "experienced engineer" as the dictates of good design and construction in civil engineering. But it is herein emphasized that such exalting fails to recognize the true nature of Man as an animal, and of Society as an inexorably impelling corollary. Moreover, both Practice and Precedents always presuppose some hypotheses of Principles. The very desire to repeat a design embodies a principle, for instance, that what is, is good. If Design is Decision despite Doubts, it is inevitable that Decision is catalysed by Desire, and Desire is seldom (or never?) random.

Thereupon, Principles is what should dictate our approach to designs. Principles have been generated step-by-step, which is an inevitable burden: but at the other extreme lies the beckoning light that Principles really represent an abstraction of idealized knowledge and wisdom, applicable to a wide range of cases. So, hypothetically, at each instance we have the obligation, and the means, not merely to go from the particular to the general case, but also from the general to the particular. For the past decades we have been continually alerted that Principles are not deterministic, but statistical. I shall put forth my brief recommendations regarding the place of statistics in Principles of Design. Truly, despite the decades of warning, statistical thinking has not really begun to flavour our handling of theoretical Principles.

Thereupon, on the basis of present fairly well accepted Principles I shall discuss what seem to be the main Problems faced in embankment dam engineering today: many problems were illusions, some were even purposely cultivated, some were generated indirectly out of the best of intentions regarding other problems, some have not been recognized or honestly faced.

Finally my recommendations are of Prudence in the advance of notions, and of humility in recognizing what are personal errors, collective errors of the state-of-the-art, and what are situations inevitably beyond the reasonable duty of an Engineer, because optimization cannot possibly condone with the presumption of protecting against any and every possibility of problem.

Case histories represent an indispensable background to such a presentation. It is emphasized, however, that even in the analyses of case histories one must lean ever backwards in compensation for the strong interference of historical, geographical, contingency and subjective elements, in the very recording and transmission of would-be "facts".

At any given moment, if we are able to advance our Principles and Prudence far enough to accomodate the probable advance of Problems foreseeable, we should be treading a firm path in engineering Practice and staking out of Precedents.

2. PRACTICE

Practice plays a very fundamental role in any technology and/or engineering endeavour. It implies the distilling of experience into the so-called "common sense", and consequent prescriptions. Things have been done in a certain manner, and presumably would be most satisfactory if they continued being done in a similar manner. It is a very ponderous argument in the face of professionals of other branches (i.e. the lay in the specific specialty), obliged to judge, select, decide. Since most dam engineers (owners, designers, contractors, and consultants) have to act at the call, decision, and acceptance of other professionals (administrators, politicians, bankers, planners, and so forth) it is very important to emphasize some of the gross fallacies in the simple arguments in favour of Practice. Practice does imply a theory and Principle, and probably the most foolish of all: that what is, can continue to be, satisfactorily, without our facing the need to analyse and understand.

Practice is never static, but changes and grows continually. It is strongly influenced both by historical conditions, by temporary conditionings, and by the continued call of the nature of Man and Society to new challenges and to pushing forward the frontiers of impunity. Thus, whereas in principle Practice would embody the respectful constant repetition of things done, in practice it contradicts itself by always serving to push forward,hopefully by imperceptible increments. And sooner or later we are faced with the last straw that breaks the camel's back, a given Practice has been over-extended to the point where other parameters have become more conditioning.

Let us consider just two obvious examples.

2.1 Plasticity

When we imagined that it was of interest to employ earthcore materials of "high plasticity" we automatically fell into several fallacies historically comprehensible and pardonable, which must first be brought out by self-analysis and honest confession.

What was really desired was the ability of the material to deform to large strains without fissuring (First Approximation).

(a) Desired = high Plasticity ≅ (1) high deformability without fissuring.

Setting aside the criticisms on the (yet present) index tests on liquid and plastic limits (Plasticity Index Tests) as presumably applicable to compacted clay embankments, the first obvious association (merely due to the identity of the word Plasticity) was to assume that good plasticity was associated with a high Plasticity Index PI% (Fig. 1).

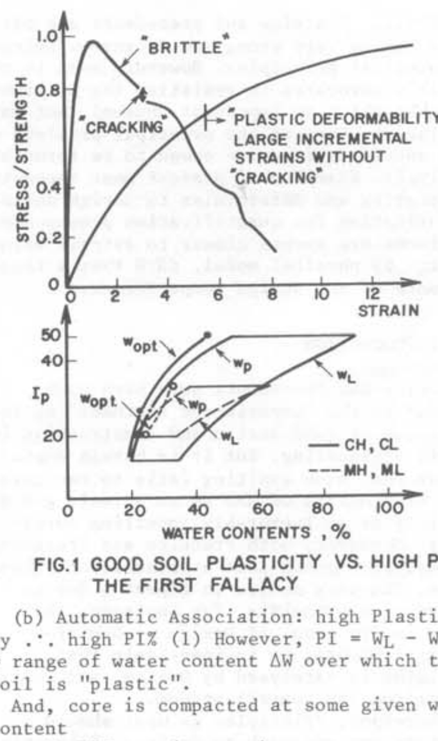


FIG.1 GOOD SOIL PLASTICITY VS. HIGH PI- THE FIRST FALLACY

(b) Automatic Association: high Plasticity .·. high PI% (1) However, PI = $W_L - W_p$ = = range of water content ΔW over which the soil is "plastic".

And, core is compacted at some given water content

$W_c \approx W_{opt}$ (suppose)

(c) What logic is there in the association derived from reshuffling of words?

Soil "plastic" over big range $\Delta W \overset{?}{=}$ soil of big "plastic" stress-strain behavior at given W_c.

(d) At any rate, assuming that $W_c \approx W_{opt}$, a second approximation reasoning could be to compare W_{opt} vs. W_p (de Mello, 1973) since W_p is an indicator of W at "similar" tendency to fissuring under major straining under atmospheric pressure, that is, simulat ing conditions near the crest or surface. And one can reason why in critical zones of core contact we gain by using $W_c \overset{\sim}{>} W_{opt}$ (e.g. $W_c \approx 1.1\ W_{opt}$) is indirectly the desire to be at water contents above the plastic limit (Fig. 2).

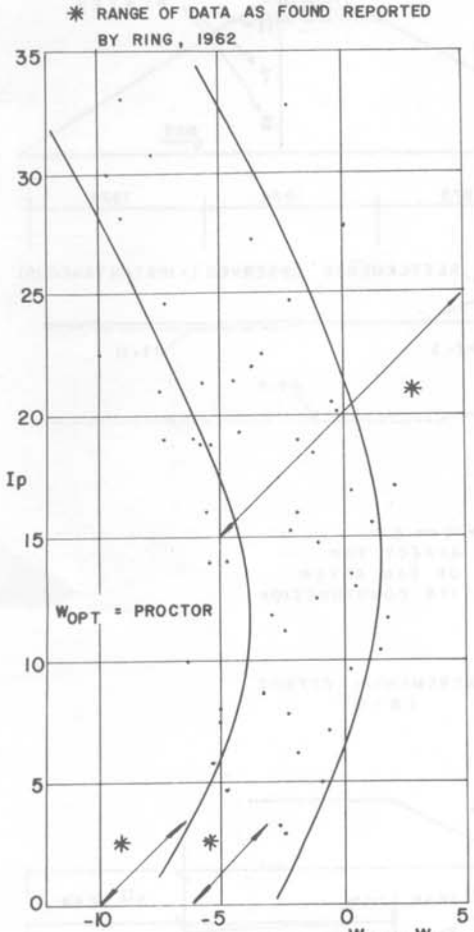


FIG.2 DATA FROM CLAYEY RESIDUAL SOILS. COMPARISON OF WATER CONTENTS AT OPTIMAM PROCTOR COMPACTION, WITH RESPECTIVE PLASTIC LIMIT.

(Second Approximation) Desired $W_c > W_p$ (2)

(e) Finally, we must still reason that what was and is really desired is not connected with any generalized fissuring under large strain, but principally protection against tensile cracking beyond some moderate strains.

Therefore, everything that causes tensile cracking upstream-downstream should matter. Of course, that includes the stress-strain curve, and thus directly includes (i) initial stresses built-in by compaction and partly retained (ii) the changes of stresses (iii) change of consequent strains (with time).

But, what compelling association is there with the stress-strain curve of a conventional "triaxial" (i.e. really biaxial) test? Even in such tests, has it not been repeatedly demonstrated that deformability moduli are quite different in extension vs. compression tests?

(f) And, if we are truly concerned with tensile cracking strains, is Δ(total external stress) or Δ(overburden stress) the only agent causing them? What about shrinkage, collapse, solution, colloid chemical action in void structure, and other volumetric strains generated quite independently of external (easily recognized) stress changes?

(g) As a first step, what is most effective is to resort to a dominant physical change of statistical universe: for instance to design so that only compressions and shears can occur, and/or to design for use of a material of such low shearing strength that movements and distortions are entirely taken up by shear. One cannot "crack" in tension a body of liquid ($s = 0$) or of pure cohesionless sand ($s = 0$ at $\sigma' = 0$).

(h) To conclude the design discussion, let us summarily apply my DESIGN PRINCIPLE 5, DP5 (de Mello, 1977): "For every behaviour desired and assumed check what happens, of consequence, if it is not successful". In mentally checking what would happen if we accept that some tensile cracking might still occur, we would promptly recognize that what we really want is high erosion-resistance of the clay (coupled with moderate erodibility and selective clogging ability of the upstream cohesionless transition): that means high cohesive strength which depends on ϕ' and the compaction preconsolidation pressure p_c.

(i) In short, in revising the simple primitive Practice of requiring a high PI material, it appears that a heavy (high p_c) wet ($W_c > W_p$) compaction of a material of high PI and low W_L (presumed higher ϕ') is a present approach to the desirable core material towards the top (where cracking can become tensile rather than shear). But consequent "rigidity" is highly undesirable if the top of the core be subject to delayed differential settlements. (Fig. 3)

And there are absolutely no test data supporting such intuitions on an all-important material detail. How to optimize

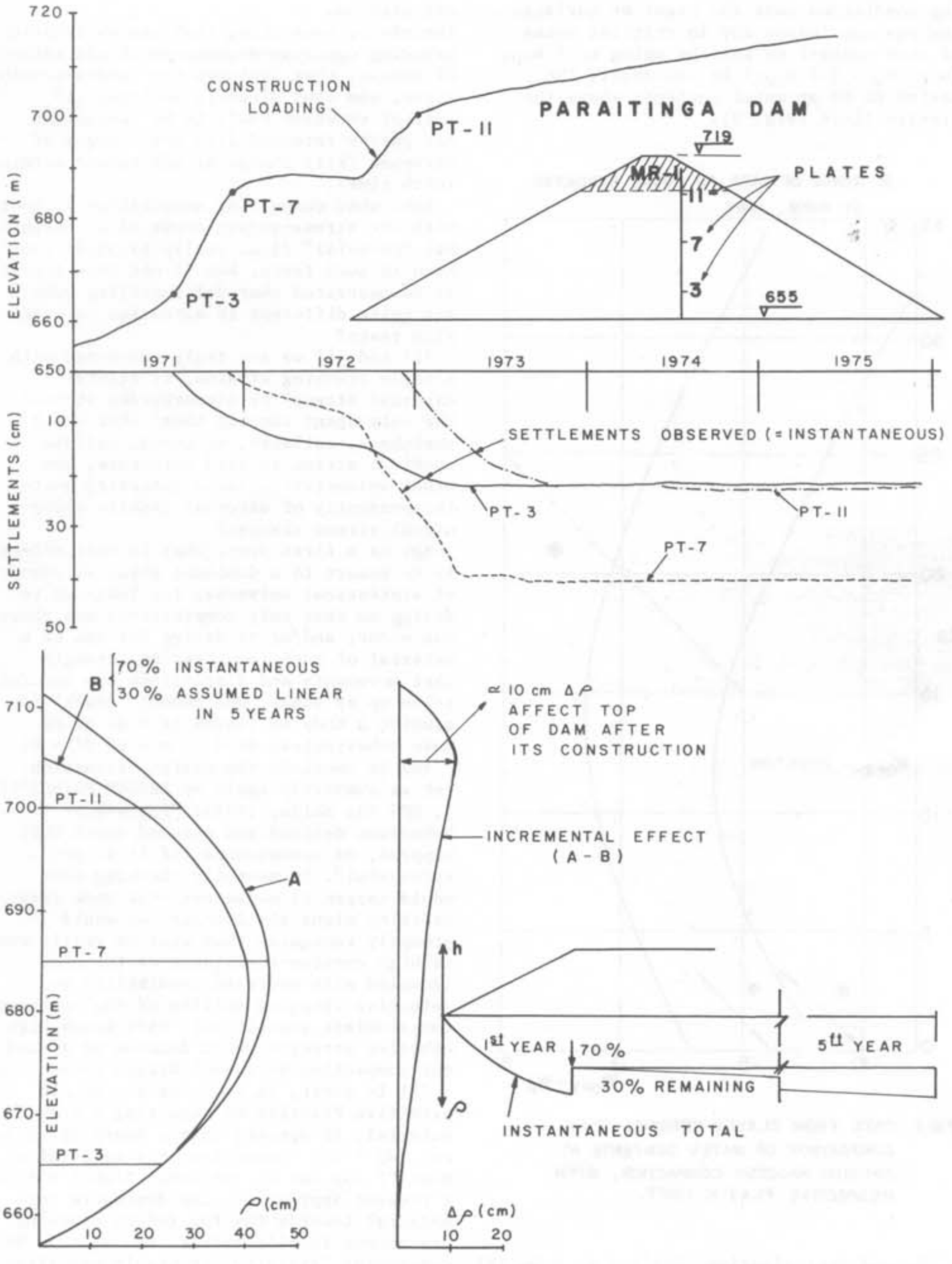


FIG. 3 IMPORTANCE OF DEFERRED SETTLEMENTS ON BEHAVIOR AT TOP OF DAM (EXAMPLE FROM PARAITINGA DAM DATA)

between frequently conflicting requirements? Engineering of dams must go on, while research institutions delay in furnishing the needed backup.

2.2 Dominance of visual-tactile culture

Practice is dominantly influenced by visual impressions, i.e. impressions at the time of building the dam, under visual-tactile observations that "are not more than skin-deep" (at $\sigma = 0$). Three obvious factors of such thinking have been mentioned (among others).

2.2.1 Homogeneity

Practice has automatically assumed that a material that is placed and constructed "homogeneous" will continue to behave as homogeneous (irrespective of being subjected inexorably to changes under different stress trajectories). However, it is obviously quite to the contrary, because any material that is constructed homogeneous, but before operation is subjected to different stresses and strains, will during operation behave as dutifully non-homogeneous. One first example to be noted concerns flownets. The idealized theories (e.g. flownet) required our assuming that a compacted clayey dam constructed as a "homogeneous section" would have a constant permeability across the section: inexorable fallacy (de Mello, 1977). Since the material compresses (settles) to different void ratios, it may indeed follow homogeneous laws of behaviour e vs. σ and k vs. e, but ipso facto the body of the dam becomes law-abidingly "heterogeneous" in permeability. (Fig. 4)

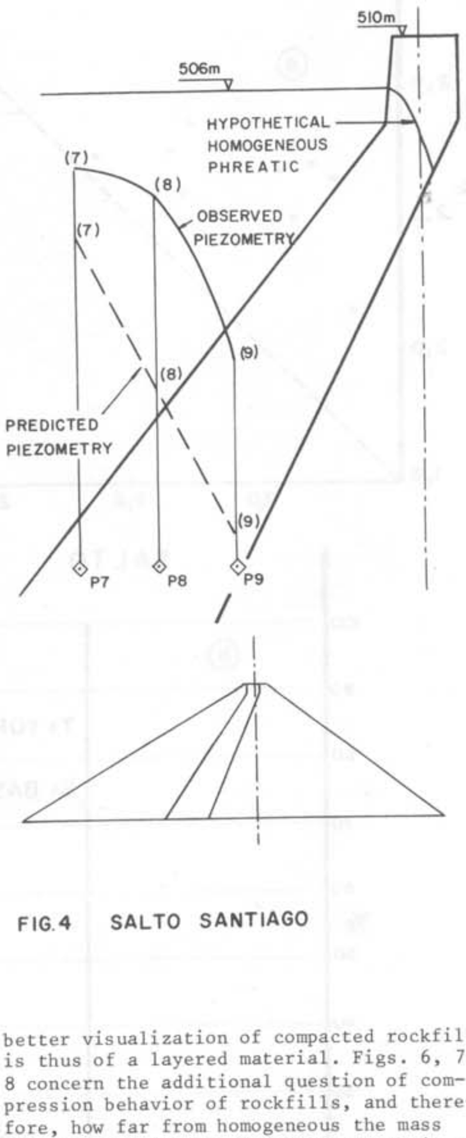


FIG.4 SALTO SANTIAGO

Fig. 4 (Salto Santiago dam) presents data that are being noted more regularly in higher dams, indicating that a disproportionate amount of head loss takes place close to the inner end of the core. The fact that in upstream-inclined cores the compression, and therefore imperviousness, increases significantly towards the downstream face, would make such behavior reasonable. Of course, the seepage effective stresses will further affect the permeabilities and the flownet through a "secondary" effect.

A further very significant example of absolutely false intuitions of homogeneity concerns compacted sound rockfills, that have been mentally associated to a "big--size uniform sand". Fig. 5 gives data from the Salto Santiago dam confirming what true rockfill designers and builders know well, that each layer comprises two distinct sublayers, in grainsize and densities. A better visualization of compacted rockfill is thus of a layered material. Figs. 6, 7, 8 concern the additional question of compression behavior of rockfills, and therefore, how far from homogeneous the mass will finally behave. Routine calculations on rockfill compressions (for moduli E) have assumed incremental stresses as directly the additional height of fill γh above the point: it is important to recognize the stress transmission influence factor I, and we may well use (Fig. 6) such factors from elastic solutions for the small increments. One immediate conclusion is that many a "delayed settlement"

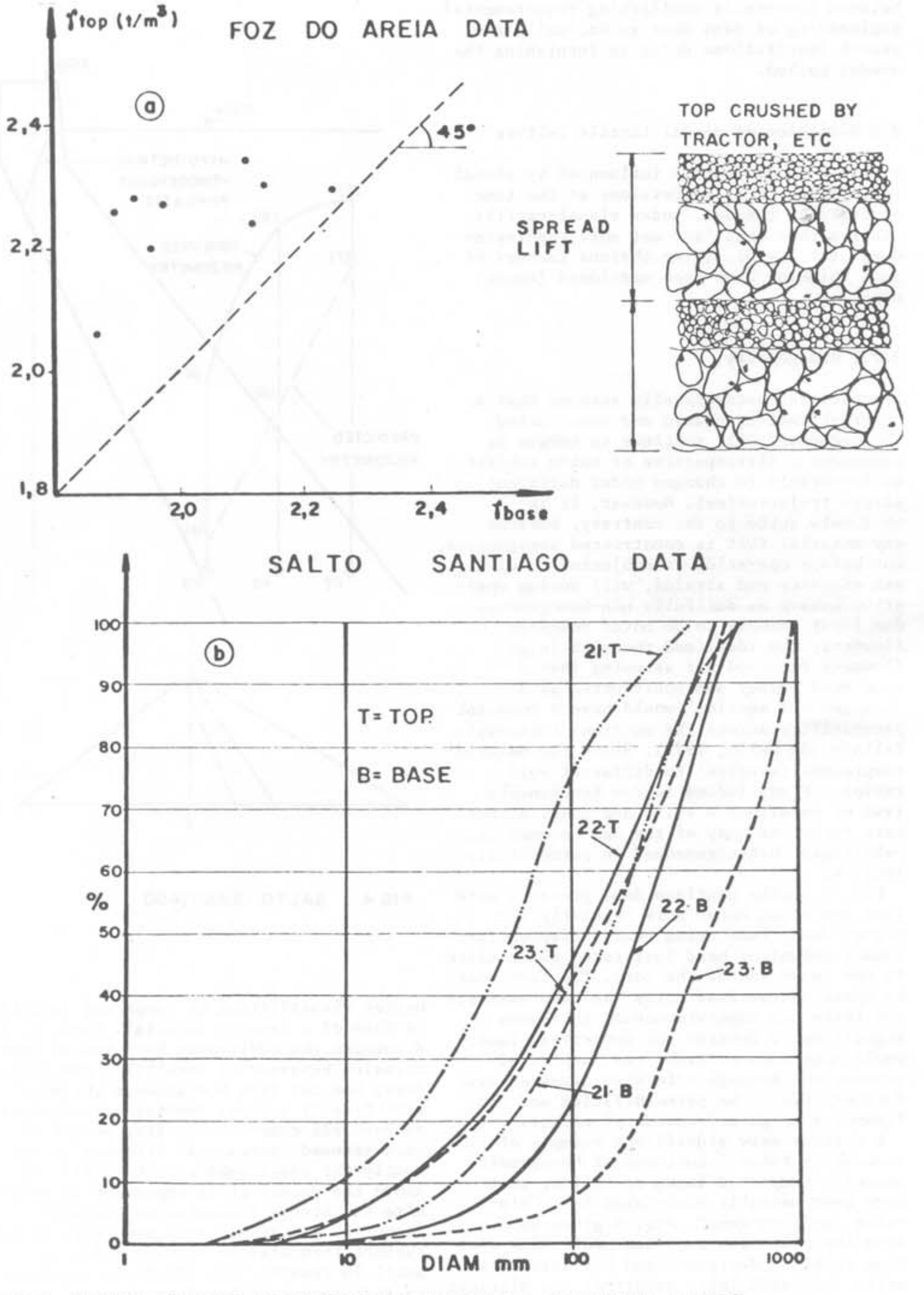
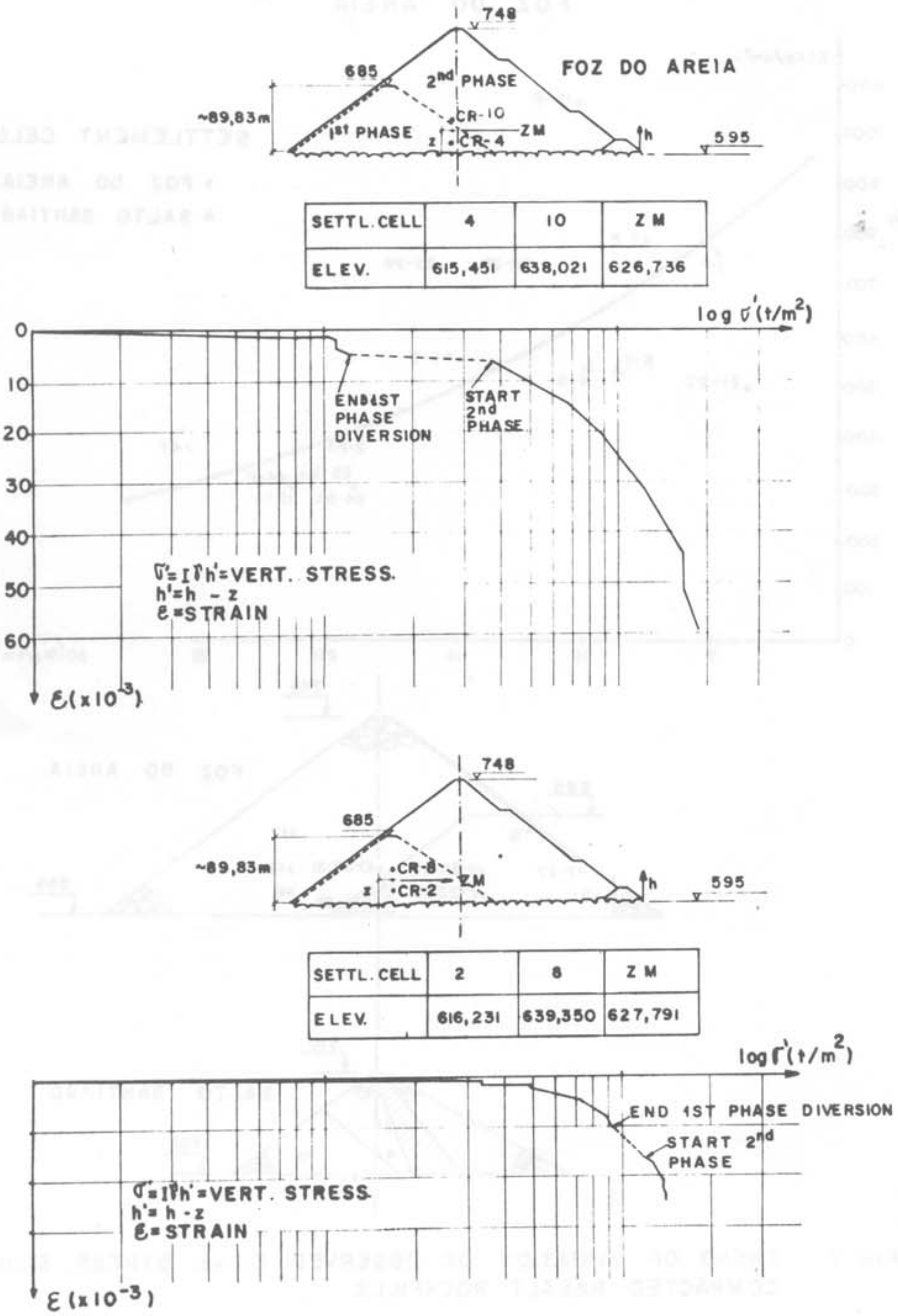


FIG.5 COMPARATIVE DENSITY TOP-BASE ON ROCKFILL LIFTS



SETTL. CELL	4	10	Z M
ELEV.	615,451	638,021	626,736

SETTL. CELL	2	8	Z M
ELEV.	616,231	639,350	627,791

FIG. 6 DETAIL STRESS- STRAINS COMPUTED EXEMPLIFYING.

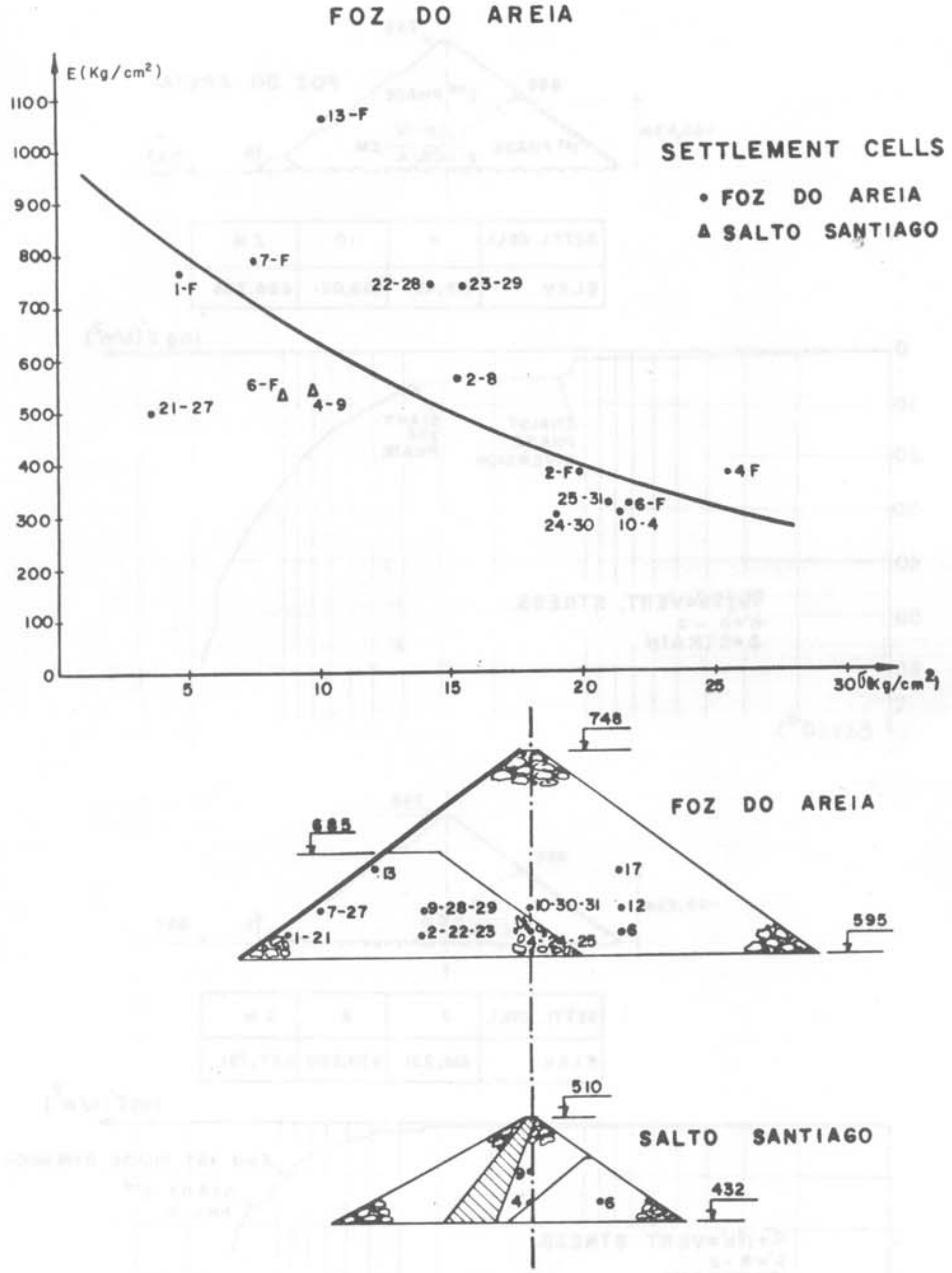


FIG. 7 TREND OF VARIATION OF OBSERVED E vs. STRESS, SOUND COMPACTED BASALT ROCKFILLS.

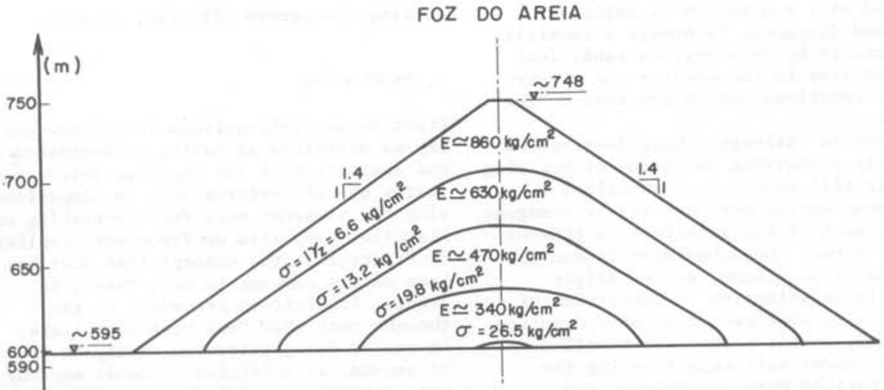


FIG. 8 FIRST CYCLE APPROXIMATION STRESSES FROM HOMOGENEOUS ELASTIC SOLUTION (POULOS + DAVIS) AND MODULI E VARYING "AS OBSERVED"

attributed to secondary compression, because fill directly above the point on the same vertical had ceased, is really found to be due to incremental stresses thrown by fill rising nearby. Another point, mentioned in an accompanying paper, is the apparent precompression pressure due to compaction. Finally Figs. 7 and 8 exemplify the very significant change of E with pressure, and therefore the dutifully non-homogeneous condition of the rockfill mass when the water load will come on the upstream concrete face. Incidentally, in a separate paper it is shown that the E moduli applicable for calculation of deformations under the hydrostatic load of reservoir filling, are obviously not the same E moduli as deduced from settlement observations of the rockfill under self-weight.

2.2.2 Geometric similitude

As I have repeatedly shown (de Mello 1972, 1977, etc.) in connection with slopes and crossections we find that our view of obeying Practice boils down to as simple and nonsensical a Principle as that of geometric similitude or even similarity. Satisfactory slopes are established as 1 on 2.0 or 1 on 2.5 etc. irrespective of heights of slopes, material properties, internal drainage details, etc. Dams varying in height from 20m to more than 200m have been and continue to be designed (i.e. drawn) as geometrically similar: if anything, with a disadvantage to the high dam because crest widths are not increased proportionately.

2.2.3 Symmetry

Of all the absurdities, the one most clearly atrocious is that of employing symmetry in a dam, built for a most unsymmetrical task. Symmetry is an inevitable corollary of gravity, and therefore comprehensibly dominates our visual culture. Moreover, during construction a dam grows against gravity: we can well see the kindergarten teacher requiring boys and girls (das kind in German, neuter gender) to skip-rope alike, dressed in like shorts and T-shirts. But the main function of US and DS zones is to complement each other in facing the reality of life which is with the reservoir full only on one side, (hopefully). How could anybody ever conceive of the temporary growing function as being the dominant one, and accept as reasonable a Practice of symmetrical sections?

Symmetry creeps in most imperceptibly as Practice in many other design endeavours. It belongs to the world of visual perceptions of laws of upright survival.

2.3 Summary conclusion

In short, Practice is an illusion, unless it is interpreted.

I recently read a very studious and well-documented paper on rockfills in dams. No distinction was made, either historical or behaviorwise between dumped and compacted rockfills. In that author's interpretation of Practice a rockfill was a rockfill, undistinguished between the very fundamental types, angular, rounded, dirty, dumped, compacted etc. A question of angle of vision and distance. To others a rockfill has seemed to be an overgrown sand. Just as beauty lies in the eyes of the viewer, so do observations lie in the eyes of the observer.

Our Russian colleagues have developed a remarkably successful technique of building hydraulic fill dams out of so-called homogeneous sands. Are they really homogeneous? How much of the satisfactory flownet behavior across the embankment is due to very wide crest widths, to the slight inevitable anisotropies in deposition of films of silt over each film of hydraulic-fill sand, to the slight additional compressions under self-weight making the central portion more impervious, and finally, to foundation conditions of pervious sands? Somebody designed and built a small homogeneous sand dam without any cutoff or drain: it failed, due to seepage exiting downstream (Florida, recent).

3. PRECEDENTS

Practice as distinguished from Precedents may be described as having predominated in the exaltation of the imperceptibly-moving status quo of conservatism, in comparison with the somewhat more forward-pushing case histories supported on Precedent. Implicit in Practice is the concept that what has been and is current in many cases, is proven. Implicit in Precedent is the thought that what "has been established" in one or few previous cases may be taken as proven, as sufficiently good: and may even support some (slight) extrapolation. The respect for Precedent is an anglo-saxon outgrowth of principles of jurisprudence and law: however respectable those might be, what possible connection might they

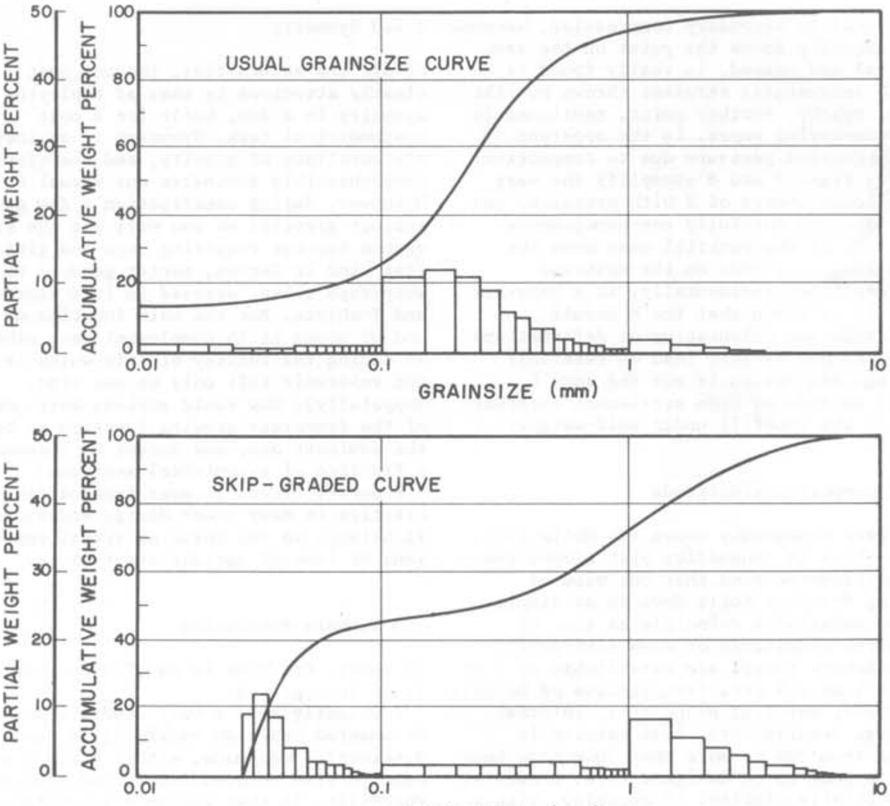


FIG.9 COMPARISON BETWEEN DIFFERENT GRAINSIZE CURVES PRESENTED AS HISTOGRMS

have with technological and statistical laws and behavior?

Inevitably, therefore, both are based on the Principle that what is, or has been, has been observed, and is satisfactory. They further imply the Prediction that what is, will be, will continue to be. Fundamental fallacies have already been discussed above:

(a) What is. Our cognizance of what is depends on the cultural tinge of the eyeglasses we happen to be wearing.

For instance, the presentation of grain-size curves in the traditional form of cumulative percentages of weights vs. log. diameters, was obviously directed towards facilitating observation of the fines. Concern centered on the fines. We easily see, however, (Fig. 9) that for the sake of impact visualization of gap-grading (de Mello, 1975 a) the preferable presentation would be by histograms of grain diameters (the latter in log scale for appropriate handling of the wide range).

How many problems and failures have been literally due to the practice of poor visual presentation of skip-graded grain-size compositions?

(b) "Has been proven". The very statement implies a deterministic causeeffect relationship that is quite fallacious. How many an action has been spared by the grace of God, or of statistics, despite its being inherently unsatisfactory? How often will we continue to test the recurrences of statistics, or the patience of God, in presuming to repeat as proven and good, what we have failed to interpret as really faulty but lucky? If Practice, applied repeatedly, fails to establish a proven Principle, Precedent (as above quoted) applied in pushing ahead as supported on few cases, can comprise an even more fallacious and dangerous concept.

(c) "Can be extended or extrapolated". Any extrapolation is always supported on the Principle of faith: and is exercised with greater confidence, and consequent ultimate danger, the greater the faith. It is of interest to compare (Hynes and Vanmarcke, 1977) the faith of few elaborate sophisticated solutions for predictions on Prof. Lambe's embankment failure problem, as compared with the audience's histogram of 26 estimates by "adjusted gut feeling". Since a significant Ingenious Engineering development frequently tends to would-be problems far beyond immediate needs (de Mello, 1975 b:118), quite often Precedent can be slowly extended for quite a stretch before finally being caught over some frontier of impunity. It is of interest to recall Terzaghi's words to Coyne regarding the Malpasset dam failure, to the effect that it could only be to a distinguished pioneer that the mishap could occur, of serving as the instrument to reveal a problem not yet brought out to the fore, in Man's gradual advance to greater needs and solutions.

Note, for instance, that when compaction of rockfill shells was developed as being good, the Swedish central-core wetcompacted earthrock dams that had behaved satisfactorily with dumped rockfills, ended up giving problems of silo effect and piping near the top.

Once again, therefore, in Precedents we recognize the intervenience of Principles -- of cognizance, of determinism, of faith, and so on.

4. PRINCIPLES

In the very discussion of Practice and Precedents we have been employing Principles, and recognizing their innate Principles. Of course, they were wrong Principles. And we now have Principles of dam design and construction; that are right: they are ours. We have Finite Element Analyses and computers.

Can we be so sure? Could it be that failures have not been mostly statistical (random), but rather very repeatedly deterministic, the main cause-effect parameter having been excessive faith in our own Principles? Was not Fontenelle Dam a dress rehearsal of Teton Dam, and both on a design crosssection faithfully employed most repeatedly? Is not each dam failure principally due to our faith that all factors have been rightly taken into account, so that "by accident" some additional factor shows up? Was Baldwin Hills a "calculated risk" or a calculated provocation?

We are, unfortunately, imbued in our likeness-of-God syndrome, and our exact-science syndrome. And faith is not scalar, but a vector: education is not scalar, but a vector. If we teach that overburden total stress is deterministically γz, armed with our deterministic faith in the Effective Stress Principle $\gamma' z = \gamma z - u$, we leap forward into solving so many earlier problems with great success that we inevitably advance confidently towards many an unrecognized engineering solution before we are shocked out of our faith, by a failure. We learn much from shocking failures, but truly what do we learn for quantification, for developing statistical laws? (de Mello, 1977).

Principles are also adjustable, and our views of Problems depend on our Principles, and our Principles depend on the Problems that did beset us.

One fundamental Principle of the engineer is that any behaviour $X = f(a, b, c, d, \ldots z)$ is always a function of infinite number of parameters, and we have to synthesize immediate solutions, Prescribed as satisfactory, for our view of a finite number of Problems rated according to Priority. Scientific investigation and analysis proceeds in a diametrically opposite trend, picking out the knowledge of the behavior of X with regard to each separate parameter, all others maintained constant. Because of our finite capacity to recognize and face problems it is always dangerous to divert attention to non-problems (the classic scapegoat technique) and it will generally happen that the next accident will be due to a different problem. Churchill said that the trouble with Chiefs of Staff of armies is that they always prepared well how to fight the last war.

In my Rankine Lecture I tried to distinguish between problems associated with Extreme Value statistics, and those belonging to statistics of averages, repetitive, permitting formulation of laws, amenable to Bayesian adjustment, quantifiable within degrees of confidence. And I postulated that in Civil Engineering remarkable or catastrophic failures are Extreme Value cases. I have heard that statement questioned.

Let us first set aside some failures as Acts of God. Mount Saint Helen's volcanic explosion should be classified as an Act of God: we cannot propose to design our dams for such eventualities.

Civil Engineering always designs for conditions far from failure, and therefore when significant failures occur they are always an "accident", something beyond existing theory, something observed, analysed, and adjusted a posteriori. Hypothesis and theses may derive prematurely from intuitions, but theory and "laws" of behavior can only be formulated by repetitions of facts. Fortunately we can derive intuitions from assumed facts: but upon closer analysis such facts will turn out to have statistical dispersions. Our quantification and adjustment must insist on seeking highly repetitive conditions: therefore Failures are excluded.

Engineering really implies a sequence:

(a) Visualization of a physical model. Observations of Extreme Value conditions, failures, constitute a great support for such visualization. Create structures that avert the feared extreme value conditions: that is, in the face of possible extreme value failures in a given physical Universe (of statistics), use a change of Universe for a solution. Design Principles DP1 and DP2, Rankine Lecture.

(b) Employ nominal design-analysis procedures and observed great number of cases for "Satisfaction Indices". This is the quantification in statistics of averages.

(c) Refine steps (b) and consequences by repeated iterative adjustments. As far as possible employ the principle of Pre-testing so as to achieve Factors of Guarantee rather than nominal Factors of Safety.

(d) Thus hopefully move forward from knowledge of computations and behaviors to the wisdom of choosing a physical model (statistical universe) that literally dispenses analysis. Presumably it is guaranteed against failure, or at least against distressing failure. We have used Design Principle DP5 in mentally checking what can happen if our hypotheses and desired behavior do not fall within the presumed range.

5. PROBLEMS

Besides the overall Problem of time-lag in our redirecting the vectors of our deep faith in our Principles of cause-effect zero-dispersion determinism, what may be some of the specific technical problems I visualize being faced in dam engineering presently? Here go some examples.

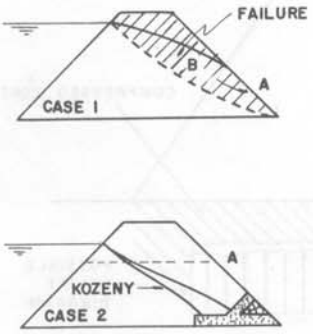
5.1 Corrective measure vs. design solution.

A good localized corrective measure to an extreme value problem is not necessarily a good overall design solution on average conditions. Exemplified by the case of filter-drainage at local seepage exits down-stream, in comparison with toe drainage (Fig. 10) (de Mello, 1977).

5.2 Variability of overburden stresses around γz.

The average value γz is inexorable. However, the simple computation is based on the hypothesis of homogeneity and no shear stresses on the sides. In the cases of the dam superstructure we well recognize the silo effect. How can we be blind to significant variations in foundations, when heterogeneous. The more rigid elements carry most of the pressure (de Mello, 1972). In a silt lens beside big boulders it is not merely a statistical dispersion, but quite deterministic: the silt was deposited due to the protection from the boulder; and receives a small share of overburden for the same reason (Fig. 11).

5.3 Strong faith in flownets, highly aver-



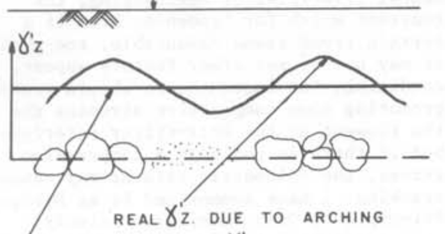
OBSERVATION	AVERAGE CONCLUSION
REPEATED FAILURES EXIT A (EXTREME) MASS B (AVERAGE)	I) FLATTER DS SLOPE..., LITTLE IMPROVEMENT. 2) TOE AND BLANKET FILTER-DRAIN OF CASE 2.
VERY INFREQUENT FAILURES; EXITS A (EXTREME)	FAILURES STILL BLAMED ON "UNUSUAL" CONDITIONS. COMPARE CONCEPTUALLY WITH SPILLWAY DESIGN FOR AVERAGE FLOOD.

FIG.10 A TOE FILTER-DRAIN RAPIDLY APPLIED AT A POINT OF SEEPAGE EMERGENCE IS AN EXCELLENT CORRECTIVE MEASURE. AS GENERALIZED DESIGN IT IS INSUFFICIENT, CANNOT PRESUPPOSE POINTS OF EMERGENCE.

aged gradients i.

In fractured rocks how valid are "triangular diagrams" of uplift pressures, drainage tunnels etc... (Fig. 12)

In heterogeneous gravel-sand alluvia, how can we use reasonings based on limiting average $i = H/L$? What difference can it make, to local piping conditions, to change blankets from 10H to (15 or 20)H? Even the concept of $i_{crit} \approx 1.0$ grossly ignores directions of vectors $\sigma'g$ to be composed with $\sigma'i$, and assumes $\gamma'z$ as average overburden.



VERY DANGEROUS FOR PIPING BECAUSE THE FINE COMPRESSIBLE SILTS ARE EXACTLY (DETERMINISTICALLY) THE ONES ON WHICH THE γ'Z NECESSARY FOR S FOR EROSION RESISTANCE, DOES NOT ACT AS ASSUMED

FIG. 11

5.4 US impervious blanket as a badly conceived structure.

Represents an oversimplified attempt to solve a very idealized partial problem, seepage. Already inefficient if one considers tridimensional deposition of gravels-sands-silts. No thought to problems of loading due to reservoir, especially if there is time-lag in establishing underlying flownet (de Mello, 1977). Requires attention to k_o (see 5.7).

5.5 Grouting and fixed-width diaphragm walls.

In my Rankine Lecture I discussed the error of the mental model of grout curtain as a fixed-width discontinuity. The inherent benefits of grouting are as a pretest treatment, more effective where most needed, and helping to exclude extreme conditions of perviousness. The diaphragm walls as presently executed are dangerous inasfar as they limit themselves to fixed width. The inherent error can be easily corrected by techniques long since developed in the grouting of alluvia.

5.6 Uniform filters, flat well-graded filter.

Design of filters for stereometric hindrance was considered a problem solved, but has turned up as a vexing problem. With well-graded non-uniform "highly desirable" materials the risks of segregation set in, depending on inexorable selectivity of construction operations. As an extreme value problem it must be solved by ap-

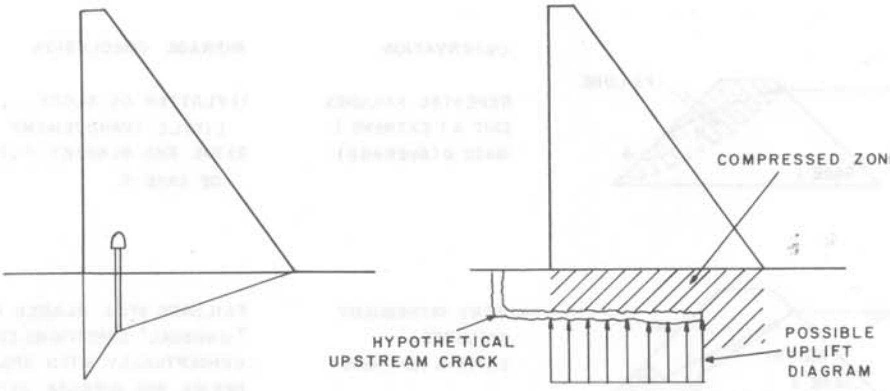


FIG. 12

propriate physical model: besides the appropriate grainsize for stereometric hindrance, promote compressive stresses (not exaggerated - cf. Prudence) in the material being filtered, so as to have increased arching, compression, resistance, around any start of washing-through.

5.7 Importance of σ'_2

Comprehensibly, while attention was directed to slope failures, the pair of stresses of interest σ'_1 and σ'_3 were in the plane US-DS. The function of the dam however, is to retain water and the principal risk is of transverse planes of low σ'_2. What do we know about this all-important item? Do Finite Element Analyses as presently available shed the necessary light? What do we know about the difference between the K_o due to external (membrane) loading, as compared with body-stress effective stress loading? Is it valid, as regards volumetric strains to consider the classic simplification (Taylor, 1948) of soil mechanics that we can consider as equivalent

Total stresses -
$-$ Boundary Neutral stresses $\overset{?}{=}$
$\overset{?}{=}$ Gravity effective stresses
σ'_g coupled with seepage effective stresses σ'_i?

Do the finite element analyses presently conducted consider the hysteresis effects?

5.8 Influence of differential settlements on tensile cracking.

The problem has been discussed for thirty years, but the all-important factor of time has not been discussed or considered. Obviously what matters is the delayed settlements that will affect the upper part of the dam (where tensile cracking can develop) after it has been built. Settlement occurring before a layer exists cannot possibly affect it.

5.9 Instrumentation for alerting on failure

A most dangerous fallacy to be guarded against is that of relying on instrumentation for indications of impending failure (de Mello, 1977). It is a most dangerous faith. Instrumentation can, and does indeed, furnish excellent information on average conditions, Satisfaction Indices.

6. PRUDENCE

These and many other serious Problems lead me to emphasize as one of the most fundamental Principles of engineering, the constant watch for Prudence. Even if a certain trend seems favourable, too much of it may not be so: other factors appear, to condition. For instance, we should prefer promoting some compressive stresses due to the flownet at the soil-filter interface: but if there is too high a compressive stress, the volumetric strains may cause cracking. I have summarized it as Design Principle 4, DP4: "Minimize untimely, uncontrollable, major and rapid, changes of condition towards problems of consequence". Indeed, from the solutions of one generation frequently arise the plagues of the next, because one of the greatest of all Problems is one placing too rabid a faith on one's Principles. We must lean over backwards to take ourselves with a pinch of salt.

An old Arab saying goes:

He who knows not, and knows not that he
knows not; he is a fool:shun him.
He who knows not, and knows that he
knows not; he is simple:teach him.
He who knows, and knows not that he
knows; he is asleep:awake him.
He who knows, and knows that he knows;
he is wise:follow him.

Upon analysis I would find that the last line would be quite comprehensible for a culture of yore. Unacceptable today. Moreover, there is one more combination that makes sense. So offer a revision:

He who knows and knows that he knows; he
is useful:use him.
He who knows and knows that he knows not;
he is wise:follow him.

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