Field Slope Charts for Stability Studies

Levé des pentes en place pour études de stabilité

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Summary

Charts for comparing field measured slopes often afford a simple approach for selecting a design strength for stability studies-basically by analyzing strength necessary to support Nature's slopes in equilibrium. For composite formations, particularly sedimentary rocks, the uncertain effects of alternating strong and weak beds, jointing and bedding make this approach more reliable than one based solely on laboratory tests. Examples are given for shales at Ft. Peck, Garrison and Tuttle Creek Dams.

Sommaire

L'inclinaison naturelle des talus en place permet dans beaucoup de cas de déterminer facilement les éléments de base des calculs de stabilité, avant tout en fournissant les caractéristiques susceptibles d'assurer l'équilibre de ces talus. Dans le cas de formations sédimentaires comportant des couches alternées de compacité différente, ce mode de détermination qui évite les incertitudes dues à l'hétérogénéité, à l'inclinaison des couches et à la nature des contacts donne de meilleurs résultats que les seuls essais de laboratoire.

Ce rapport donne des exemples relatifs aux schistes de Fort Peck, Garrison Dam et Tuttle Creek Dam.

The Design Strength Problem

Selection of a design shear strength for important cut slopes is seldom an easy problem, even for homogenous soils and with the best of boring samples and laboratory tests. This is particularly true for soft rock formations of younger geologic age such as clay-shales, chalks, lignites, poorly cemented sandstones, etc., which are nearly always overconsolidated from sediments formerly overlying and since eroded. For composite formations of alternating stronger and weaker beds, the problem is magnified several fold by the uncertain effects of jointing, faulting and similar local weaknesses and of reinforcing contributed by the stronger layers. A further complication is the tendency for samples of the weaker materials to be unsuitable for testing so that the laboratory data is, for the most part, obtained only for the stronger beds. It has been well said, that the material to worry about is not what one sees in the core box — rather it is the gap labeled "lost core" as this frequently represents material too weak for recovery. For these disconcerting conditions, the real answer desired is the "in-situ" strength of the overall slope as affected by the local weaknesses and reinforcements Nature has built into it.

In many locations, Nature herself has already provided significant in-place tests and on a far more comprehensive scale than any conceivable program of laboratory investigation on small samples. Most reliable data is that from careful analysis of existing slides; but where Nature's tests have not been carried to destruction, they are also useable. It is obvious that the strength of existing slopes is at least that required to maintain their present equilibrium. The task is to interpret Nature's "in-situ" testing under her conditions and then to apply this to our conditions, as frequently changed by the project construction.

The Field Slope Chart

An approximate but often productive approach is the field slope chart, consisting simply of a plot of slope heights vs. slope inclinations. Depending on data available, this alone may be sufficient in some cases to establish the demarcation between safety and instability. In other cases requiring further analysis, it is a convenient form for summarizing and interpreting the evidence from a group of existing slopes.

In practice, it is well to initiate the study by a geologic reconnaissance of the locality to select significant slopes in the pertinent formation for further investigation. These are then surveyed to establish slope profile, key beds of the geology and an estimate of ground water conditions. To extent practical, work should concentrate on slopes resulting primarily from the formation strength and avoid those cases where the slope has been further flattened by run-off erosion. For slides it is important to gather all evidence which will aid in estimating the slope condition berfore failure. At some particularly pertinent slopes a few borings may be justified, preferably equipped with piezometers to show seepage conditions.

Two limiting seepage cases for natural slopes are shown on Fig. 1 which it is important to recognize for subsequent analysis of the slope by the methods of soil mechanics. Case A can be expected where the formation is essentially homogeneous in permeability; it has been termed adverse since the seepage forces are so inclined that they produce a high over-turning moment for a circular slide. Case B is more likely in a stratified formation and particularly where more pervious drainage layers are present. It has been termed favorable seepage since the vertical direction of seepage forces minimizes their over-turning effect. In practice, seepage in most natural slopes is apt to be somewhere between these two limiting cases as shown by the following examples.

Bearpaw Shale at Fort Peck Dam

The simplest form of slope chart may be merely a plot of successes and failures as shown by Fig. 2. This chart was developed for the Bearpaw shale at Fort Peck Dam which is located in northeast Montana. This is a clay-shale of Upper Cretaceous age, moderately faulted and slickensided, with numerous bentonite layers and some thin limestones. More detailed properties of the shale have been reported

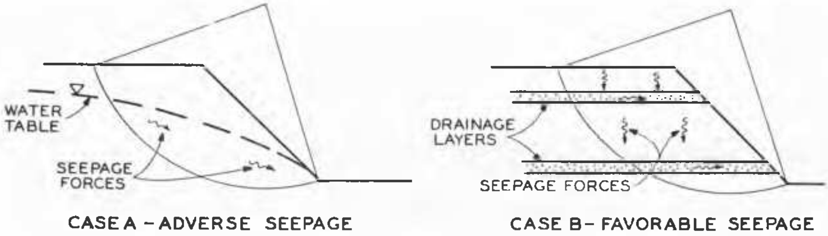

Fig. 1 Seepage cases. Natural Slopes.
Cas de percolation dans des talus naturels.

by Middlebrooks [1] and various discussors of his paper. It is quite fissile and weathers to flakes, then ultimately to a fat clay. As shown by Fig. 2, the weathered shale is far weaker than the parent material.

This chart was developed for the outlet area, principally for studies of excavation slopes during design of the second powerhouse in 1953-56. Seepage conditions approximate adverse Case A of Fig. 1. Most of the plotted slope failures occurred during excavation for the initial construction in 1934-35, when soil mechanics was in its infancy. Rarely are such a high percentage of failures available to so clearly indicate the boundary between success and failure. More commonly it is necessary to estimate the strength and resulting safety factors from data on a group of largely stable slopes as illustrated by the next example.

Fort Union Shale at Garrison Dam

The formation at Garrison Dam in central North Dakota, is the Fort Union clay-shale of early Tertiary age. While largely fat clay, some beds are silty and some uncemented sand. There are occasional horizons of limey concretions and numerous beds of lignite coal which latter are quite pervious due to their open joints. The heavy pre-consolidation load (in the order of 80 to 100 tons per sq. ft.) and other properties of the Fort Union have been previously reported by Smith and Redlinger [2].

The project involved design of some 10 miles of excavated slopes for various channels, several over 200 ft. and one 300 ft. high. Available human experience was limited to 60 ft. cuts on railroads and in nearby lignite mines. More significant was Nature's experience — numerous bluffs 200-250 ft. high on the valley walls, including several slides.

The problem was handled principally by the slope chart of Fig. 3. Survey profiles and geologic sections were obtained for some 25 slopes, including 3 slides, of which two were susceptible to detailed analysis. Different values of friction and cohesion were then tried as a process of curve fitting to locate the strength best suiting the basic slope data. Use of Taylor's [3] charts for stability number made it comparatively easy to construct trend lines of equal safety factor for different assumed combinations of friction and cohesion.

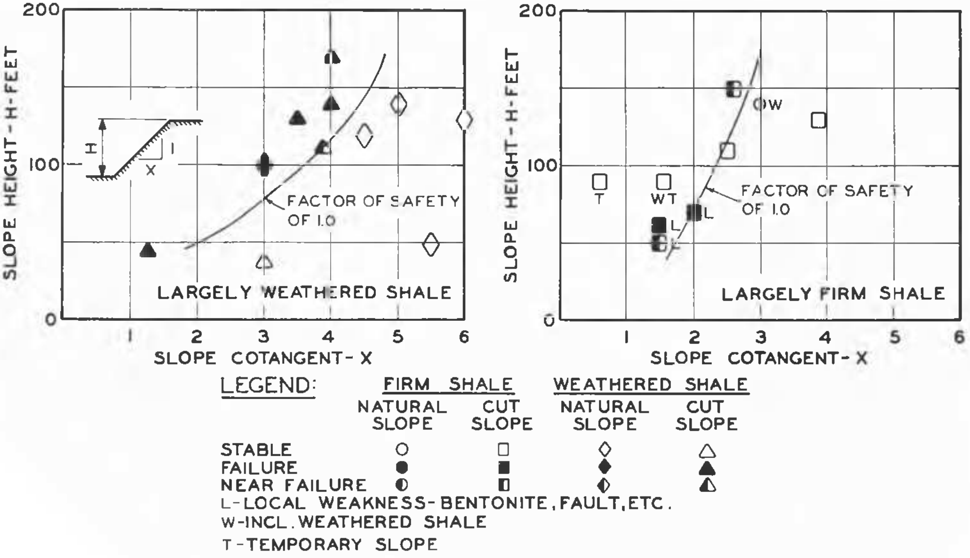

Fig. 2 Bearpaw Clay-Shale at Ft. Peck Dam.
Argile schistifiée type Bearpaw au barrage de Ft. Peck.

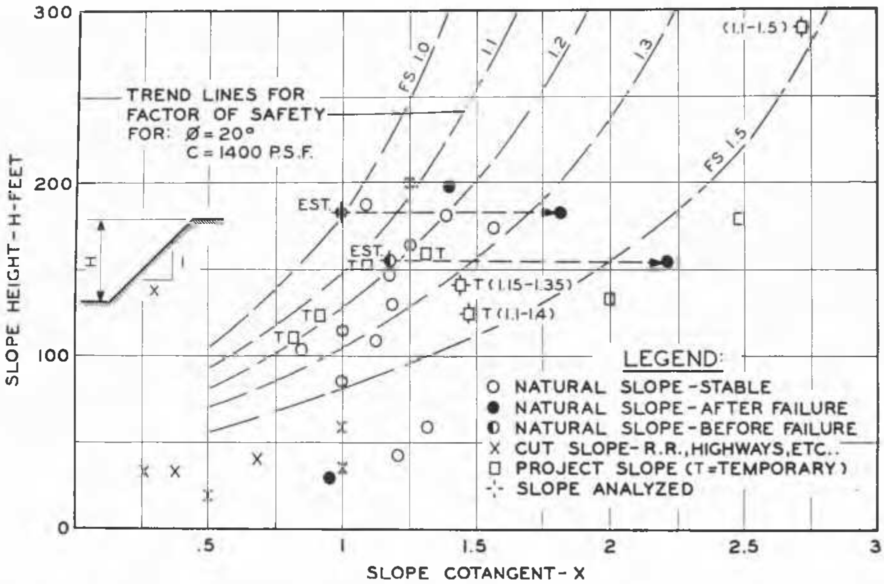

Fig. 3 Ft. Union Clay-Shale at Garrison Dam.
Schiste argileux type Fort Union à Garrison Dam.

With the lignites acting as horizontal drains and since the natural slopes were cut slowly over thousands of years by erosion of the river valley, favorable seepage Case **B** was considered most applicable. This corresponds to the case Taylor terms "capilary saturation" using saturated unit weight. Design values of $\Phi = 20°$ and $C = 1\,400$ lb. per sq. ft. were selected as best fitting the slope data and were also fairly well supported by laboratory tests. Fig. 3 shows trend lines of different safety factors computed from Taylor's charts for favorable seepage Case B.

The chart also shows several of the more significant project slopes, including some temporary ones where a lower safety factor was admissible. The more important of these were subjected to detailed analysis for the two seepage cases of Fig. 1, assuming :

Case A with inclined seepage might occur in event the slope is cut very rapidly.

Case B with vertical seepage is likely to develop eventually, particularly where the lignite drainage layers are favorably located.

For most slopes, best estimate of safety factor was considered to lie between these two limiting cases. Safety factors for 3 slopes from these analyses are shown on the chart in parenthesis — the first and lower value for Case A, the second and higher value for Case B. It is interesting that the Case **B** safety factors closely check those derived for the same case from Taylor's chart.

With the design strength thus derived (principally from the field slope chart of Fig. 3) other charts for slope design were prepared for seepage Case A and B and then used for actual slope design. Upstream slopes were further flattened and checked for the drawdown case, which gave a lower safety factor than Case A. The design thus based on Nature's slopes was entirely successful; in 12 years since construction, there have been no failues of the Fort Union slopes. Neither has the design seemed over conservative as one temporary slope over the dowstream tunnel portals exhibited border line performance. For this slope, special portals were constructed to offset the reduction in strength during the period the tunnels were mined as holes [4].

Shale-Limestone at Tuttle Creek Dam

At Tuttle Creek Dam in east central Kansas, the bedrock is much older and harder and was excavated by blasting. The formation consists of alternating beds of shale and limestone of Permian age. The limestones are comparatively hard, some beds of riprap quality, and due to their open joints are the feebly permeable members of the formation. Water concentrating abilities of the limestones were well illustrated by bands of more prolific vegetation following the limestone outcrops — good evidence that seepage conditions approached favorable Case **B**.

The problem was to design slopes for the spillway channel up to 120 ft. high. Geological reconnaissance showed available experience in the same formation limited to an 80 ft. railroad cut and a 45 ft. high road cut, plus a few lower slopes — all stable as shown by Fig. 4. Lacking any failures, two assumptions were made for the highest 80 ft. existing slope; (1) limiting condition with safety factor of 1·0 and (2) a possible condition with safety factor 1·2. Trend lines were computed from Taylor's charts as shown on Fig. 4, with both conditions showing substantially the same trend. Accordingly the project slopes were set as shown on the figure and in the 4 years since excavation have been entirely satisfactory. The actual safety factor is considered to be substantially greater than assumed for the above two conditions where the cohesion was assumed comparatively low. For example, the effect of doubling the cohesion would double the slope heights for the lines representing a safety factor of 1·0. Hence this is not

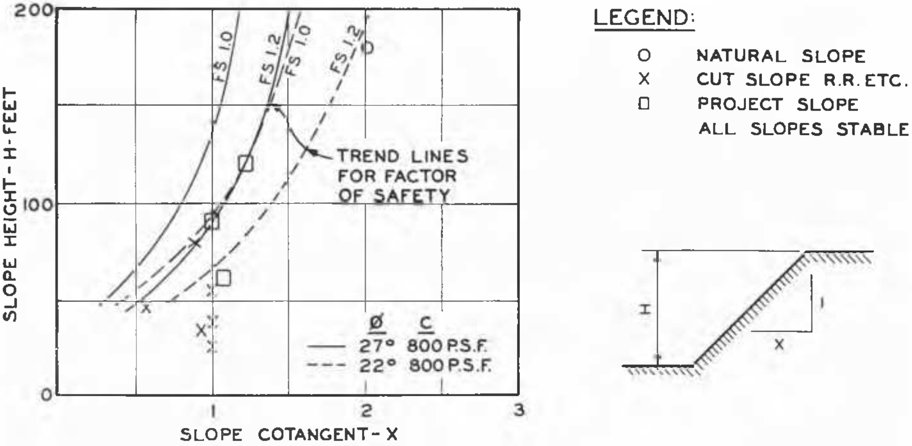

Fig. 4 Shale and Limestone at Tuttle Creek Dam.
Schiste et calcaire au barrage de Tuttle Creek.

PROJECT	FORMATION	DESIGN STRENGTH EFFECTIVE STRESS BASIS			SOURCE
		Ø	TAN. Ø	C-T/FT²	
OAHE DAM	PIERRE CLAY-SHALE WITH FAULTS AND BENTONITES	12°	0.2	0.2	EXPERIENCE WITH SLIDES
GARRISON DAM	FT. UNION CLAY-SHALE	20°	0.36	0.7	FIELD SLOPE CHART CONFIRMED BY LAB. TESTS
PANAMA CANAL	CUCARACHA CLAY-SHALE	10°	0.18	1.15	FIELD SLOPE CHART PAST FAILURES
FT. PECK DAM	BEARPAW CLAY-SHALE AND BENTONITE, WEATHERED	10.5°	0.185	0.2	EMBANKMENT SLIDE ON FOUNDATION
FT. PECK DAM	BEARPAW CLAY-SHALE AND BENTONITE, WEATHERED	10°	0.18	0.2	FIELD SLOPE CHART
FT. PECK DAM	FIRM SHALE AND BENTONITE	20°	0.36	0.2	FIELD SLOPE CHART
SOUTH SASKATCHEWAN RIVER DAM	BEARPAW CLAY-SHALE SOFT WEATHERED SHALE	9°	0.16	0.1	ANALYSIS OF FIELD SLOPES BEFORE FAILURE (TOTAL STRESS BASIS)

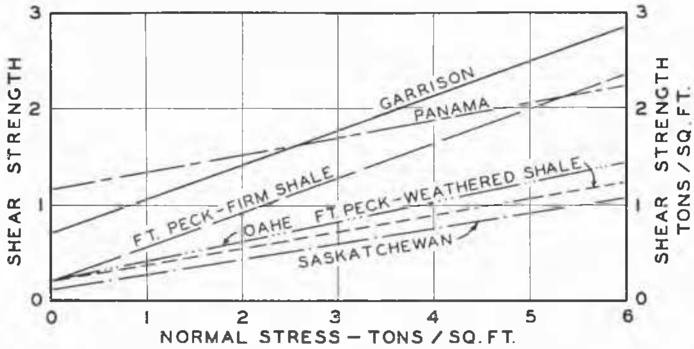

Fig. 5 Clay-Shales Design Shear Strengths.
Résista ncesau cisaillement d'argile schisteuse dans divers projets.

really an example of estimating a design strength from the slope chart; rather it is included to illustrate use of the chart for extrapolating from stable slopes to cuts of greater height.

Conclusions

Examples have been selected to indicate various methods of applying a field slope chart for stability studies of excavated slopes. They illustrate how a moderate effort with such approach paid dividends in slope design at three of the world's largest earth dams. While these applications cover soft rocks, the chart approach is also useful for soil slopes, particularly in interpreting slide failures. The charting of field slopes is not a panacea nor a replacement for laboratory testing, but can serve to guide judgment and to supplement the laboratory and geologic data in a quite positive way. It follows the philosophy that the most reliable answer is often provided by "in-situ testing" — in this case by seeking to interpret Nature's large scale in-place tests.

Special credit is due Mr. C. K. Smith (formerly Head, Soils Section on design of Garrison Dam) for further developing the chart approach as previously applied on the Panama Canal [5]. As a matter of interest, design strengths for clay-shales in Panama, U.S. and Canada [6] are compared in Fig. 5 — in all cases derived from field slope charts or from analyses of slides and hence considered more reliable than values solely from laboratory tests.

References

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