ANALYTICAL STUDIES OF PANAMA CANAL SLIDES

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SUMMARY.

The East and West Culebra Slides alone contributed more than 50,000,000 cubic yards of additional excavation to the task of building the Panama Canal. These slides occurred in the Cucaracha formation, the weakest rock encountered along the Canal, largely poorly bedded, variably bentonitic, slickensided, soapy-textured clay shales.

From available cross sections showing monthly excavation progress during construction, three sections through the slides were selected for study. The geology of each section was determined from drill holes and surface reconnaissance. Stability analyses of the conventional Swedish circle type were applied to the East and West Culebra slopes as they existed immediately before slides in 1912 and 1915, and also to the slope of 1947, which is apparently stable.

The slopes were analyzed in two ways. First, assuming factors of safety of approximately 1.0 just prior to any failure, the avaibale shear strength was deter minedfor each date for comparison with the strength used in the design of excavation slopes for a new canal. Second, the values for the cohesion and angle of friction of the Curaracha, as used in the latest slope design studies, were used to determinedfactors of safety of the sections before any slides had occurred. The factors of safety were found to be less than 1.0, indicating that the strength assumtions used were consertive.

"....the catastrophic descent of the slopes of the deepest cut on the Panama Canal issued a warning that we were overstepping the limits of our ability to predict the consequences of our actions." This statement was made by Dr. Terzaghi at the opening of the First International Conference on Soil Mechanics and Foundation Engineering in 1936, at which time little had been done towards applying the analytical methods of soil mechanics to the study of these disastrous slides,

Since that time, two projects have required that extensive study be given to these slides and to the materials in which Panama Canal slopes had failed, in order that slopes safe against sliding might be designed in the same materials. From 1940 to 1943, a special engineering organization of the Panama Canal was designing and beginning to construct new sets of locks, a project which involved large excavations in the critical, incompetent materials in which slides had previously formed. This project was suspended because of the War, and its completion is not now considered likely. During 1946 and 1947, the Panama Canal conducted the Isthmian Canal Studies - 1947, a comprehensive investigation into the problem of increasing the capacity and security of the Panama Canal. In the study of the feasibility of a sea-level canal at Panama, cuts more than 600 feet deep were found to be necessary through the very region where the slides of the original canal construction had been most serious.

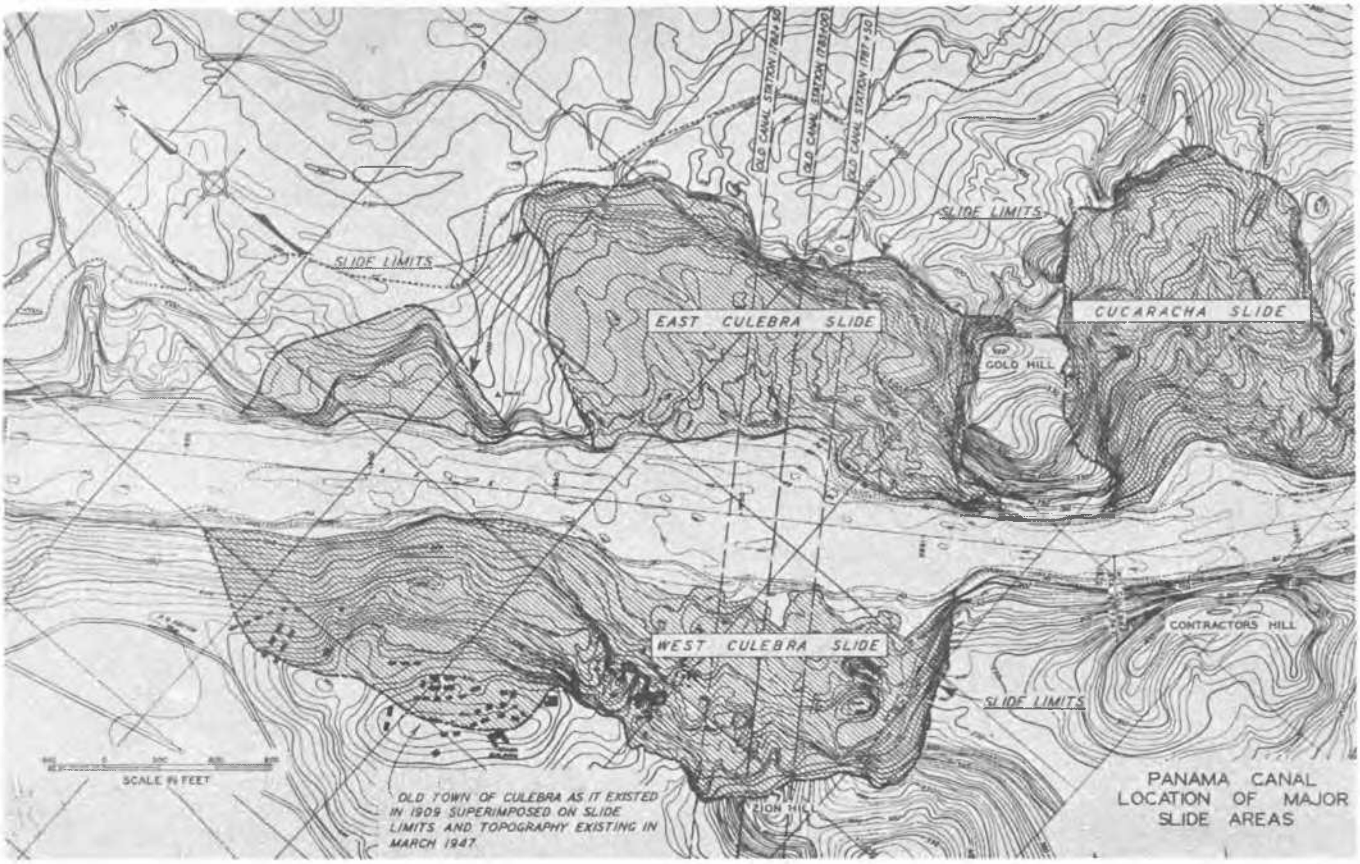
Of all the Panama Canal slides, the most disatrous were the great East and West Culebra Slides, the locations of which are shown on Figure 1. These two slides alone contributed more than 50,000,000 cubic yards of additional excavation to the task of building the Canal. On January 1, 1916, their areal extent was 70.5 and 60.8 acres, respectively. Figure 2 gives some indication of their destructive nature. In this paper will be described certain analyses of these two slides, the results of which were used in the design of slopes for an improved Panama Canal.

These slides had their apparent beginnings in 1907, when cracks were noticed back of the top of slope, followed by bulging at the bottom of the Cut. They continued to show major actively until 1916. Since that date, their activity has consisted only of slow sporadic flows into the Canal prism. This flow, for the most part, has been easily handled by dredges and has gradually tapered off until there remains now only a very slight annual movement.

THE CUCARACHA FORMATION.

Both of these slides occurred in the Cucaracha formation, which is exposed extensively along the Panama Canal near the Continental Divide. The maximum known thickness of this formation is 625 feet. Its composition is dominated by weak, poorly bedded, variably bentonitic, slickensided, soapy-textured clay shales (altered impure tuffs) interbedded with soft to medium hard, fine, tuffaceous siltstones; medium to coarse, cross-bedded sandstones; pebble conglomerates; thinly bedded, often lenticular, soft, clayey lignitic beds; and one hard bed of agglomeratic, indurated tuff. The formation largely represents an accumulation of fine volcanic detritus that has been reworked by stream action and subjected to a partial chemical decomposition of its component ash particles with resulting creation of hydrous clay minerals of the montmorillonite-beidellite group. It is the weakest rock formation encountered along the Panama Canal.

The clay shale phase is the predominant member of the formation and comprises from 40 to 60 percent of the total. This clay shale is a soft to medium-hard, soapy, highly bentonitic material, usually gray-green in color, although purple, and green and purple, mottled variations occur. The clay shales all appear to be disturbed, and they contain many degrees of slickensides and fractures or joints. Some of the fractures and joints show secondary mineral fillings. Blocks of the clay shale taken from an excavation are usually completely bounded by shiny slickensided surfaces and can be broken down with the hands into many smaller pieces, also bounded by slickensided surfaces. During drilling, standard NX core



Panama Canal location of major slide areas.

FIG.1

East Culebra slide showing upheaved material between stations 1746 and 1758. Looking south, Febr. 6, 1913.

FIG.2

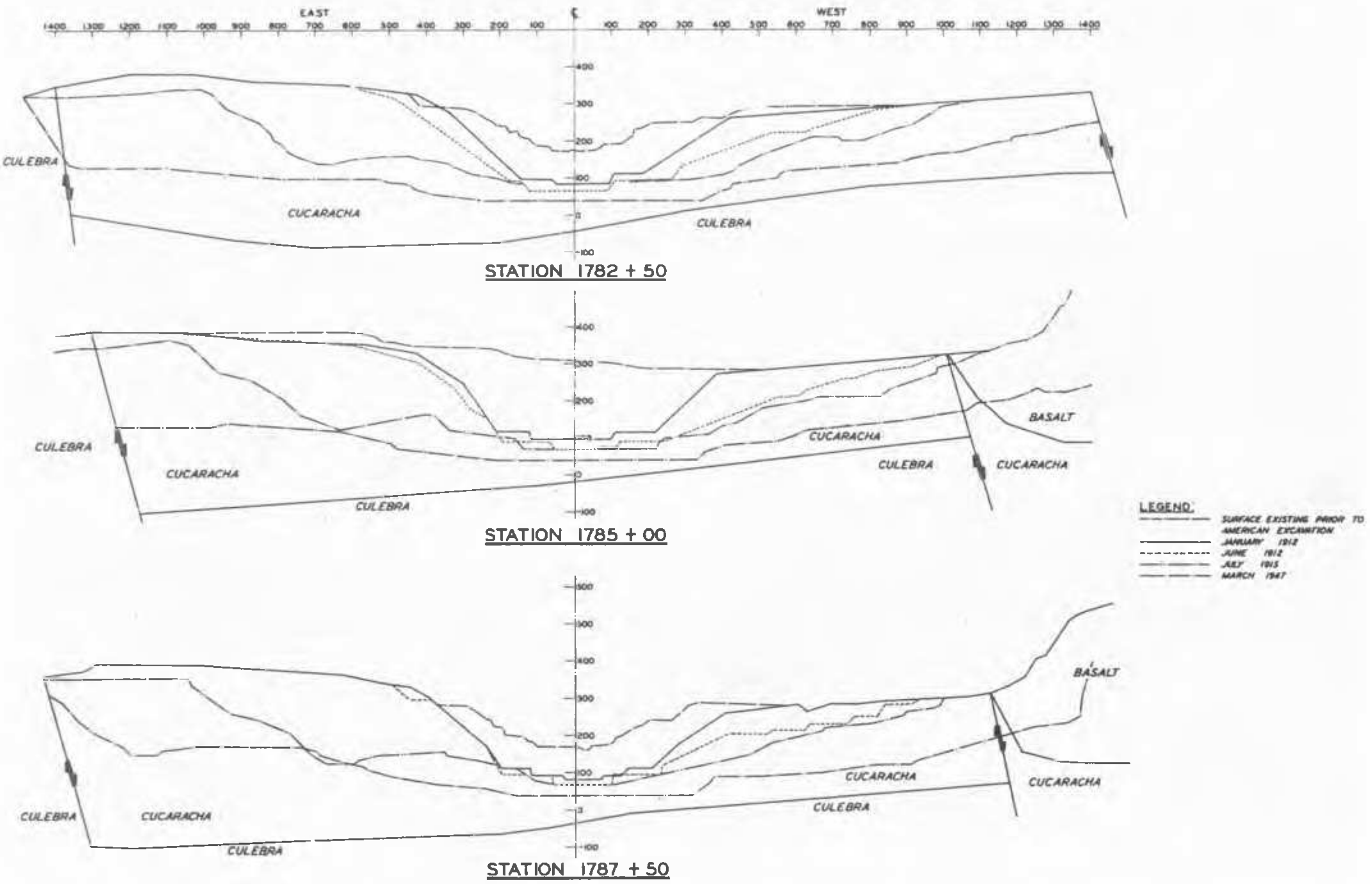
(2-1/8-inch diameter) breaks into pieces ranging from one inch to 10 inches in length along highly polished, variably inclined surfaces. Badly crushed, gougelike zones of varying thicknesses have been encountered in virtually every exploratory drill hole reaching these shales. A zone of such material having a thickness of more than five feet, the largest one thus far discovered, was found in a testpit excavation. The material in this zone was so soft that it flowed into the excavation even when the wall bracings were carried within one foot of the bottom of the shaft.

Solid clay shale has an average unit natural (saturated) weight of 135 to 140 pounds per cubic foot, an average dry weight of 115 to 120 pounds per cubic foot, and an average moisture content (percent of dry weight) of 17 to 18 per cent. Badly crushed and gouge-like clay shales have unit wet weights as low as 120 pounds per cubic foot and moisture contents as high as 30 to 35 per cent. The specific gravity and voids ratio of the clay shale can be computed from the unit weight and moisture content. Assuming that the rock is 100 per cent saturated with water, the specific gravity of the solid clay shale is 2.7 to 2.9 and the voids ratio (ratio of volume of voids to volume of solids) is about 0.5.

SLIDE ANALYSIS.

For use in the analytical study, canal cross sections showing the monthly progress of excavation during the construction period were available. Three sections were selected for study at the locations shown on Figure 1. The geology, as determined from drill holes and surface reconnaissance in the area, was then plotted for each section. By the use of these cross sections, together with topographic maps of the period, it was possible to determine the ground surface as it existed at dates preceding each slide movement.

The excavation records and other reports



STATION 1782 + 50

STATION 1785 + 00

STATION 1787 + 50

East and West Culebra slides progress of slide movement.

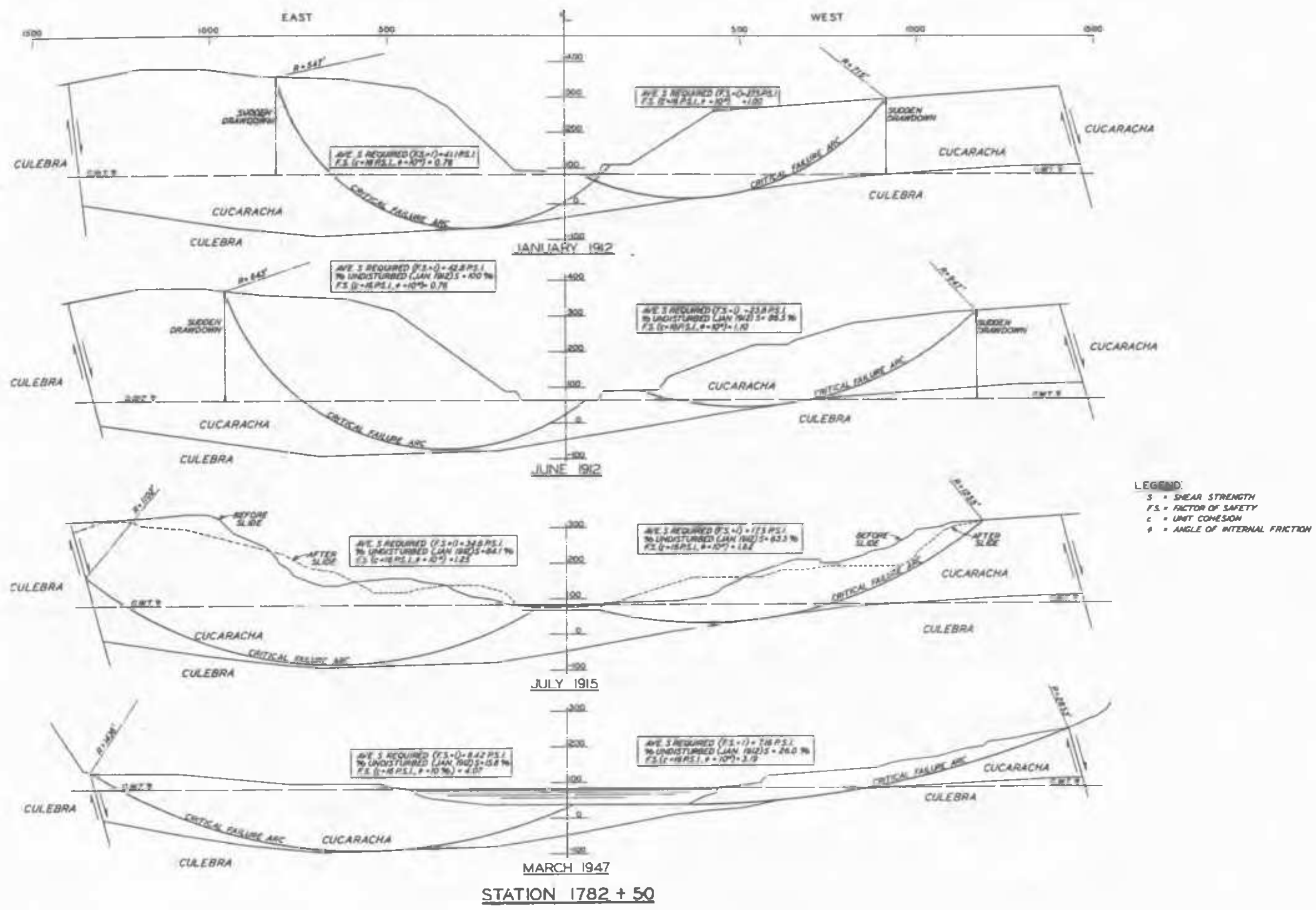
FIG.3

indicate that no major slides occurred in the immediate area under study prior to Januari 1912. Static stability analyses of the conventional Swedish circle type were applied to the east and west Culebra slopes as they existed in January 1912, June 1912, Juli 1915, and March 1947. Slopes as excavated on the above dates were analyzed as slopes which were just stable. The slopes as shown in Figure 3 for January 1912, June 1912, and Juli 1915, did not remain stable but were shortly subject to major sliding. The March 1947 surface has existed essentially as shown for a number of years and is apparently stable. The slope failure surfaces were assumed for the purposes of the analyses to be confined to the Cucaracha formation, failures known to have occurred in material bordering the Cucaracha being considered, for the most part, to be secondary surface failures not originally involved in the major slides.

In the analysis of any slope which has failed, it is ordinarily assumed that the slope must have had a factory of safety of approximately 1.0 just prior to failure. The shear strength found by analysis of the January 1912 slope is assumed to be the undisturbed shear strength of the material, while the shear strength required for the March 1947 slope is assumed to be the final residual shear strength of the material. The 1947 surface on the west bank of the Canal has been altered to some extent in some locations by dredging, but within the accuracy of the studies presented herein, it can be assumed to be the natural slope reached by the sliding mass. A condition of sudden drawdown from the top of slope to bottom of cut was assumed for the analyses of the 1912 slides, because it is believed that the excavation was done over a relatively short time interval which would warrant such an assumption. There are no data available on the actual elevation of the groundwater table at that time. Water was first admitted into the Cut in October 1913, and in all studies of slides occurring after that date, the ground-water table was assumed to be at the level of the water in the Cut.

DECREASING SHEAR STRENGTH WITH PROGRESS OF SLIDES.

The familiar phenomenon of the decrease in shear strength of a clay as it is remolded is revealed by the analyses of the East and West Culebra Slides on several dates as sliding progressed. In the slide studies presented herein, the shear strength required to give the slope a factor of safety of 1.0 has been calculated for the most critical circle at various stages of sliding. The shear strength obtained in each case is an average strength along the entire length of the critical failure arc. In addition to the slopes as they existed in January 1912 and March 1947, the sections were analyzed at two intermediate stages of sliding in order to gain information concerning the rate of decrease in shear strength of the material involved in the slides. On Figures 4, 5 and 6. cross sections



East and West Culebra slides-stability analyses-station 1782 + 50.

FIG.4

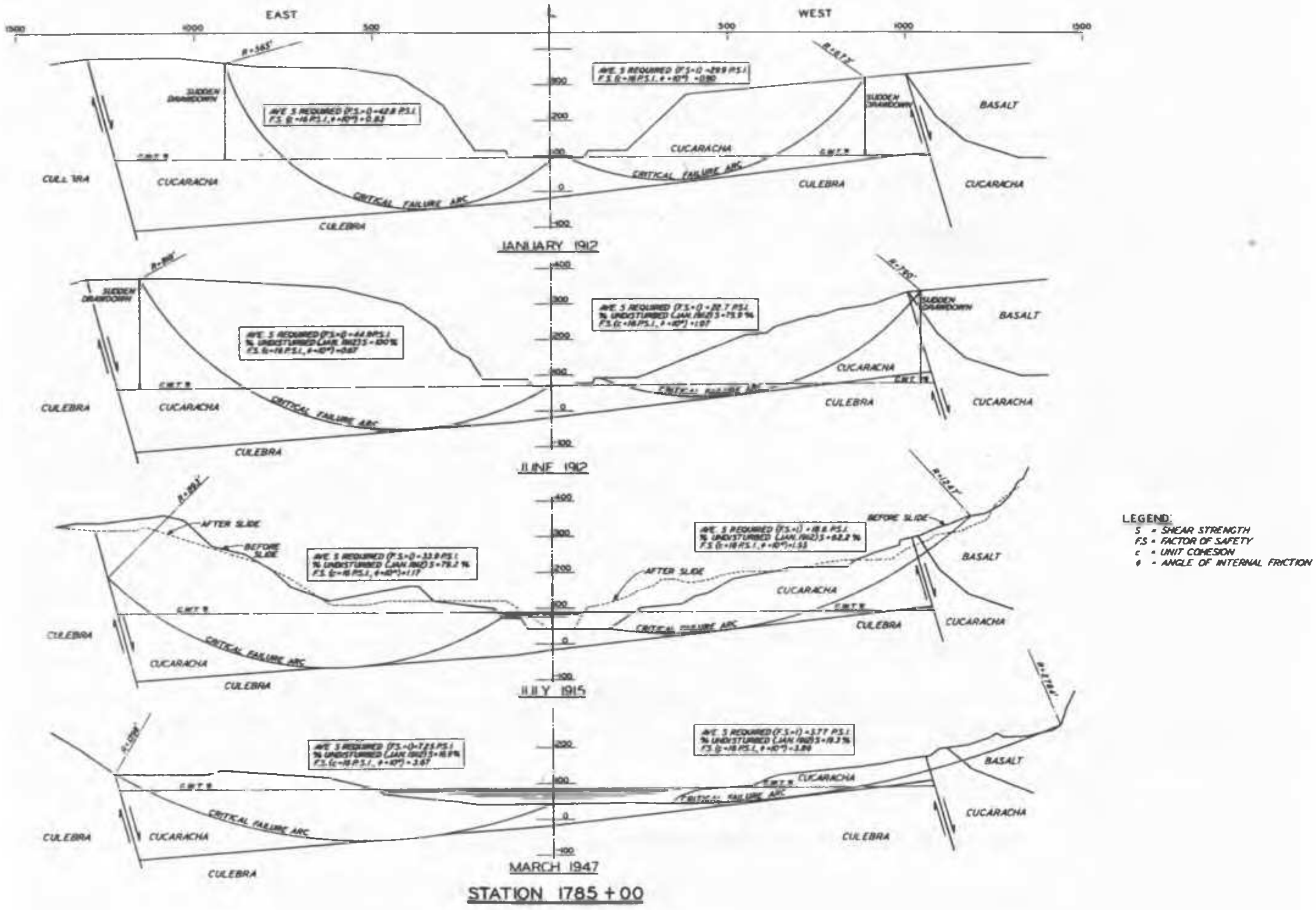
of Stations 1782-50, 1785-00, and 1737,50, respectively, are shown with results of analyses thereon. In Figure 3 it may be seen that the East Culebra Slide between January and June 1912 consisted merely of surface movements, but the other slides studied appear to be of the deep-deformation type.

Figure 7 is a summary of results of the Culebra Slide studies. In the West Culebra Slides the shear strength decreased on the average to 80.4 per cent of the undisturbed (January 1912) strength between January and June 1912. There was no decrease in the East Culebra strength for the same period. During the period from June 1912 to July 1915, the shear strength dropped to an average of 78.6 per cent on the east bank and 65.6 per cent on the west bank. During the last period from July 1915 to March 1947, the shear strength dropped to 20.3 per cent on the east bank and 23.7 per cent on the west bank. The final average residual shear strength of the material for both the East and West Culebra Slides was found to be 22 per cent of the undisturbed (January 1912) shear strength, the range for the cases studied being 15.6 to 28.3 per cent.

VERIFICATION OF DESIGN SHEAR STRENGTH FOR CUCARACHA.

In the planning of a sea-level canal, slopes which would have to be excavated in the Cucaracha formation have been designed according to the curve shown in Figure 8. This curve, a plot of required cotangent of slope versus depth of cut, is based on a factor of safety of 1.3, an assumption of sudden drawdown, a unit weight for Cucaracha of 135 pounds per cubic foot, and strength values for the Cucaracha of cohesion, c, = 16 pounds per square inch, and angle of friction, φ, = 10°. This friction angle was determined from sliding friction tests made on blocks of solid clay shale polished to simulate slickensides. The value of 16 pounds per square inch for the cohesion was then determined from analysis of a standing bank of a cut about 200 feet deep in Cucaracha, on the west side of the Canal just south of Zion Hill.

In order to check the design slope curve, the apparent factors of safety of the various sections were computed using the same value of cohesion equal to 16 pounds per square inch, and angle of friction equal to 10 degrees. From the results of these studies, Figures 4 through 7, it appears that the slope curve shown in Figure 8 is conservative for the design of statically safe slopes. For the three January 1912 sections of the East Culebra Slide studies, the average apparent factor of safety was found to be 0.79 ranging from 0.76 to 0.83. For the three West Culebra Slides on the same date, the average apparent factor of safety was found to be 0.98, ranging from 0.90 to 1.05. If the actual factor



East and West Culebra slides-stability analyses-station 1785 + 00.

FIG.5

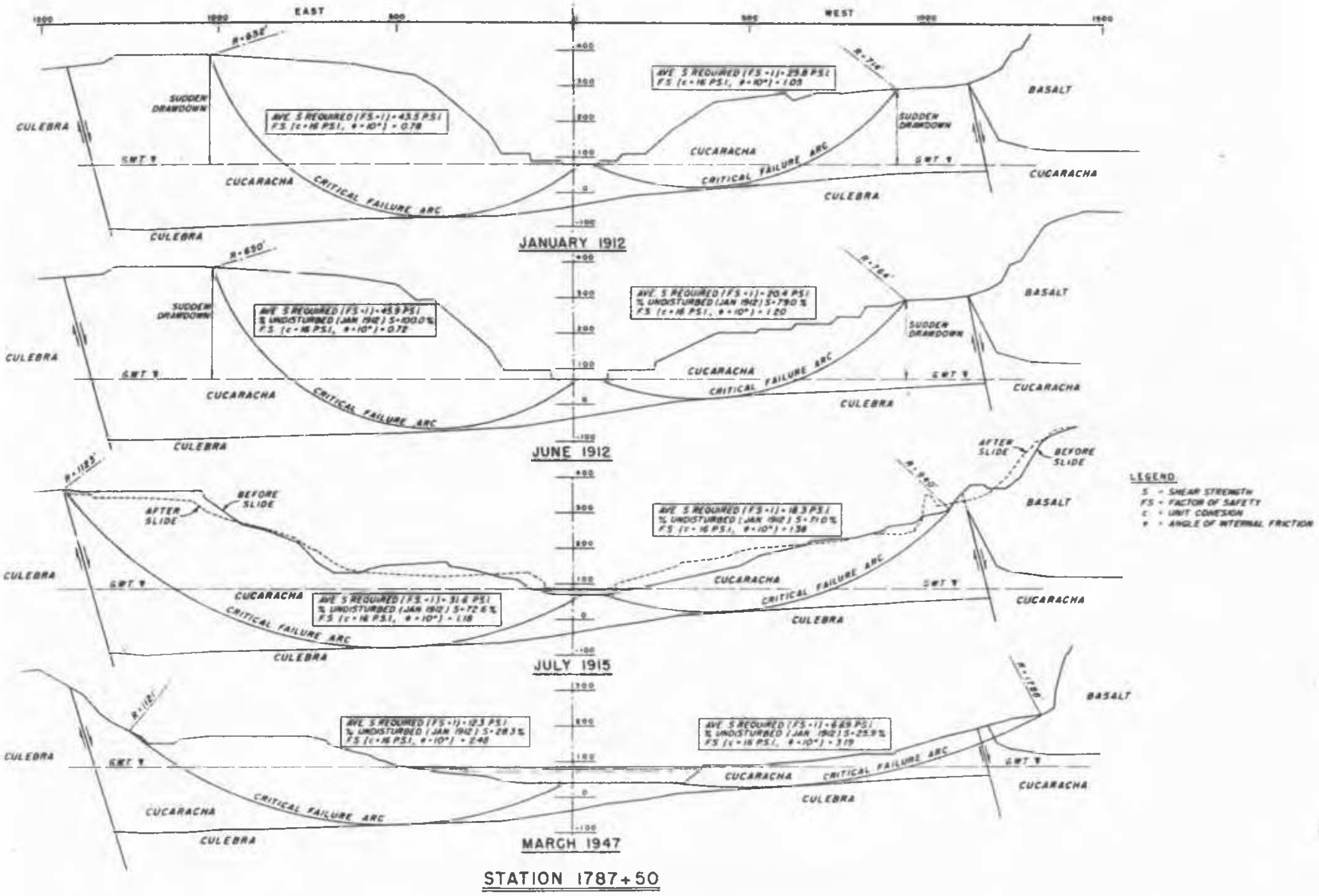
of safety in these cases approximated 1.0(as it must have, since the major slides had not started) then the strength assumption $\varphi_{,} = 10^{\circ}$, c = 16psi) used must be conservative. Therefore, the design factor of safety of 1.3 for the present Cucaracha slope curve, based on the same assumptions, may furnish an actual factor of safety higher than 1.3. The present design slope curve would require slopes for the east bank approcimately four times as flat as those actually cut prior to Januari 1913. Since it is observed that in January 1912, the east slopes were apparently more severely oversteepened than the west slopes, when compared with the present Cucaracha slope curve, it is to be expected that the factors of safety of the east side would prove to be lower than those on the west side. This was found to be so, as mentioned above. The apparent factor of safety, using present design criteria, was calculated for each section on each date studied and was found to increase as the slope becomes flatter. These values are given in Figure 7. An increase in the apparent factor of safety as the failure progresses is, of course, to be expected, because the factor of safety is computed on the basis of the undisturbed design shear strength while the overturning forces diminish.

CONCLUSIONS

The evidence of these slide studies is that the shear strength of the Cucaracha formation can drop, due to successive sliding failures, to about 22 per cent of its original value. It would appear, also, that the slope curve shown in Figure 8 is conservative for the design of safe slopes in the Cucaracha formation. It is further apparent, from an examination of Figures 3 through 7, that once a slope in Cucaracha fails as a result of having been cut oversteep, it will then assume an angle of repose much flatter than would have been required originally for a safe design.

ACKOWLEDGMENTS.

Mr. T.F. Thompson, Chief, Geology Section, the Panama Canal, was responsible for the geologic information included in this paper, while Mr. R.L. Behrend, Engineer in the Soils and Foundations Section, the Panama Canal, made most of the analytic studies. Colonel James H. Stratton directed the Isthmian Canal Studies - 1947. The author was Chief, Soils and Foundations Section, the Panama Canal, at the time these slide studies were made.



East and West Culebra slides-stability analyses-station 1787 + 50.

FIG.6

EAST

Date Slide	Height of Cut	Radius Arc of Failure	Average Shear Strength Required F.S. = 1	% Undisturbed (Jan. 1912) Shear Strength	Excavation Slopes	Apparent F.S.*	Slopes ICS–1947
Station 1782+50							
January 1912	242'	547'	41.1 psi	100	1^{v} on 1.18^{h}	0.76	1^{v} on 5.4^{h}
June 1912	249'	643'	42.8 psi	100	1^{v} on 1.37^{h}	0.76	1^{v} on 5.5^{h}
July 1915	295'	1102'	34.6 psi	84.1	$\pm$1^{v} on 1.66^{h}	1.25	1^{v} on 6.3^{h}
March 1947	60'	1436'	6.42 psi	15.6	1^{v} on 12^{h}	4.07	1^{v} on 0.7^{h}
Station 1785+00							
January 1912	237'	565'	42.8 psi	100	1^{v} on 0.95^{h}	0.83	1^{v} on 5.3^{h}
June 1912	235'	818'	44.9 psi	100	1^{v} on 0.95^{h}	0.67	1^{v} on 5.3^{h}
July 1915	291'	893'	33.9 psi	79.2	$\pm$1^{v} on 1.90^{h}	1.17	1^{v} on 6.2^{h}
March 1947	78'	1398'	7.25 psi	16.9	1^{v} on 10.4^{h}	3.67	1^{v} on 0.9^{h}
Station 1787+50							
January 1912	250'	652'	43.5 psi	100	1^{v} on 1.14^{h}	0.78	1^{v} on 5.5^{h}
June 1912	260'	650'	45.9 psi	100	1^{v} on 1.14^{h}	0.72	1^{v} on 5.7^{h}
July 1915	283'	1123'	31.6 psi	72.6	$\pm$1^{v} on 1.57^{h}	1.18	1^{v} on 6.1^{h}
March 1947	143'	1121'	12.3 psi	28.3	1^{v} on 5.50^{h}	2.48	1^{v} on 3.0^{h}

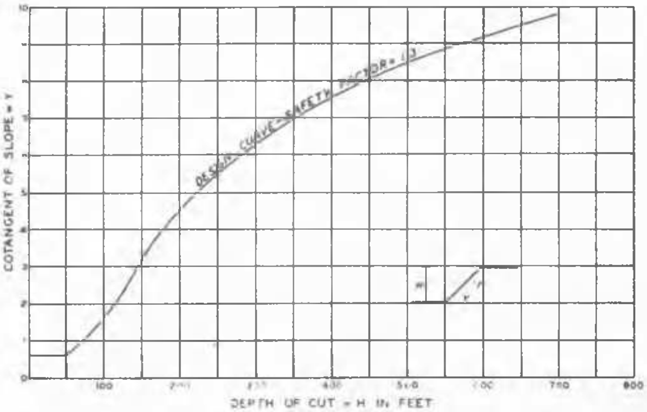
WEST

Date Slide	Height of Cut	Radius Arc of Failure	Average Shear Strength Required F.S. = 1	% Undisturbed (Jan. 1912) Shear Strength	Excavation Slopes	Apparent F.S.*	Slopes ICS–1947
Station 1782+50							
January 1912	180'	715'	27.5 psi	100	1^{v} on 1.44^{h}	1.00	1^{v} on 4.1^{h}
June 1912	232'	947'	23.8 psi	86.5	1^{v} on 3.70^{h}	1.10	1^{v} on 5.2^{h}
July 1915	265'	1255'	17.5 psi	63.5	1^{v} on 3.46^{h}	1.62	1^{v} on 5.8^{h}
March 1947	204'	2853'	7.16 psi	26.0	1^{v} on 4.8^{h}	3.19	1^{v} on 4.6^{h}
Station 1785+00							
January 1912	178'	673'	29.9 psi	100	1^{v} on 1.00^{h}	0.90	1^{v} on 4.0^{h}
June 1912	247'	790'	22.7 psi	75.9	1^{v} on 3.40^{h}	1.07	1^{v} on 5.5^{h}
July 1915	170'	1247'	18.6 psi	62.2	1^{v} on 3.54^{h}	1.55	1^{v} on 3.8^{h}
March 1947	146'	2784'	5.77 psi	19.3	1^{v} on 6.4^{h}	3.89	1^{v} on 3.1^{h}
Station 1787+50							
January 1912	165'	714'	25.8 psi	100	1^{v} on 1.27^{h}	1.05	1^{v} on 3.7^{h}
June 1912	132'	764'	20.4 psi	79.0	1^{v} on 1.7^{h}	1.20	1^{v} on 2.6^{h}
July 1915	304'	940'	18.3 psi	71.0	1^{v} on 4.2^{h}	1.38	1^{v} on 6.4^{h}
March 1947	85'	1780'	6.69 psi	25.9	1^{v} on 5.0^{h}	3.19	1^{v} on 1.1^{h}

*Note: The apparent factor of safety was computed assuming for Cucaracha: cohesion, c, = 16 psi; angle of internal friction, ϕ, = 10°.

Summary of analytical studies of East and West Culebra slides.

FIG.7



Cucaracha formation-excavation slope curves

FIG.8

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SUB-SECTION IV d

MISCELLANEOUS

IV d 1

STABILIZATION OF RIVER BANKS

W.E. DORAN, B.A.

The present paper is concerned mainly with problems of stabilization of river banks and flood embankments in the lowlying fen districts of East Anglia, an area of some 1,300 sq. miles in extent, situated a short distance inland from the Wash on the eastern coast of England. The position and extent of the area is shown in Fig. 1, in which the hatched area represents the peat covered fenland basin, the surface of which is at about mean sea level. Between the peat fens and the coastline of the Wash the surface formation consists principally of silt land of marine origin which lies at a level considerably higher than that of the peat fenlands. The fenland deposits which have been laid down in alternate periods of depression and elevation of land level relative to that of the sea, consist typically of the upper peat; a fen clay known as "buttery clay", believed to have been deposited under lagoon-like conditions and consisting of a mixture of fine silt and clay particles, and finally, a lower peat formation overlying the primary floor of the jurassic clays, Greensand, or Gault, or,in some places, boulder clays or glacial gravels.

Across this low lying fen area flow the river systems of the Great Ouse, Nene, Witham and Welland in embanked channels. The normal water level in the rivers is about six feet to twelve feet above land level, while in times of high flood, the rise above normal may be six or seven feet. The tidal waters entering the fenland rivers from the Wash are heavily charged with fine silt of marine origin which forms the main deposit on the bed and banks of these rivers. On the River Great Ouse the tide is excluded from a large part of the river system by sluices.

Two different kinds of a stabilization problem may arise, either singly or in conjunction, in connection with the maintenance of these river systems. The first type is concerned with the stability of the river bank or flood embankment as a whole, and the second with the stabilization or protection of the surface only.

On the tidal reaches of the rivers slips are liable to occur in the river banks. A typical case of such a slip on the River Great Ouse is illustrated in Figs. 2. This slip has been investigated by Skempton. 1) Remedial treatment consists in depositing a berm of slag or stone at the toe of the bank slope so as to provide sufficient weight to render the bank stable. If the bed of the river consists of very soft silt, it is advisable to sink a willow and brushwood mattress upon which the stone or slag may be deposited. Consideration must be given to the possibility of further erosion of the bed being caused by the construction of the stone berm and, if necessary, the mattress may be extended beyond the berm to provide the protection required.

It is also necessary to pay attention to the alignment of the berm so as to reduce as far as possible the formation of eddies which might give rise to new slips at either end of the work, and for this reason any abrupt projection must be avoided.