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required without supplementing the grouted area with cement grout to provide a stable curtain is questionable.

However, cationic asphalt emulsion is available in various penetration grades. The rapid setting Type CRS-1h used at Morrow Point had a penetration grade range of 85-100. The use of a lower penetration grade asphalt would have produced a harder residue possibly with improved characteristics including increased resistance to creep. Further research and tests should indicate the penetration grade best fitted for different conditions of which temperature would be an important factor.

Due to the asphalt adhering to moving parts in pumps, injection from air-pressurized tanks is more effective. The injecting operations should be continuous without interruptions until refusal because an interim of a few minutes may cause premature plugging.

The ratio of emulsion and lime slurry is critical in regard to breaking time. Tests using varied ratios and site water with similar temperatures are recommended to determine the optimum ratio that fits the requirements for travel distances.

Journal of the

SOIL MECHANICS AND FOUNDATIONS DIVISION

Proceedings of the American Society of Civil Engineers

ANALYSES OF WACO DAM SLIDE

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INTRODUCTION

In October, 1961, the construction of Waco Dam was interrupted by the occurrence of a slide along a 1,500-ft section of the embankment resting on the Pepper shale formation, a heavily overconsolidated, stiff-fissured clay. A photograph of the 85-ft high embankment section, taken shortly after the slide occurred, is shown in Fig. 1. The failure surface extended over 700 ft downstream from the axis of the dam, passing a considerable distance horizontally through the Pepper shale and exiting upward toward the surface through an apparently weakened zone of the foundation (1). In the slide region, the Pepper shale had been geologically uplifted to the surface and was bounded laterally by two faults crossing the axis of the embankment. The slide was confined to the length of the embankment founded on Pepper shale, and no significant movements were observed beyond the fault boundaries.

Following the slide, the embankment was degraded to a height of approximately 40 ft, and an extensive investigation was carried out by the U.S. Army Corps of Engineers to determine the cause of the failure. The results of this thorough investigation, which have been summarized by Beene (1), showed that low residual shear strengths and unusually high pore pressures in the Pepper shale explained the failure of Waco Dam. On the basis of these studies the embankment was successfully redesigned using effective stress analyses and low residual strength values.

The investigation also indicated that the failure of Waco Dam could not be explained by using total stress analyses based on strength values measured in conventional unconsolidated-undrained triaxial compression tests. The study described herein was undertaken to examine in further detail the undrained

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shear strength of Pepper shale and the use of total stress analysis procedures for predicting the short-term stability of embankments founded on heavily overconsolidated stiff-fissured clay shales.

UNDRAINED SHEAR STRENGTH OF PEPPER SHALE

Undisturbed samples of the Pepper shale from the Waco Dam foundation were obtained for testing through the courtesy of the U.S. Army Corps of Engineers' Southwestern Division Laboratories. The Pepper shale is a highly plastic, dark gray compaction shale which upon close examination reveals a

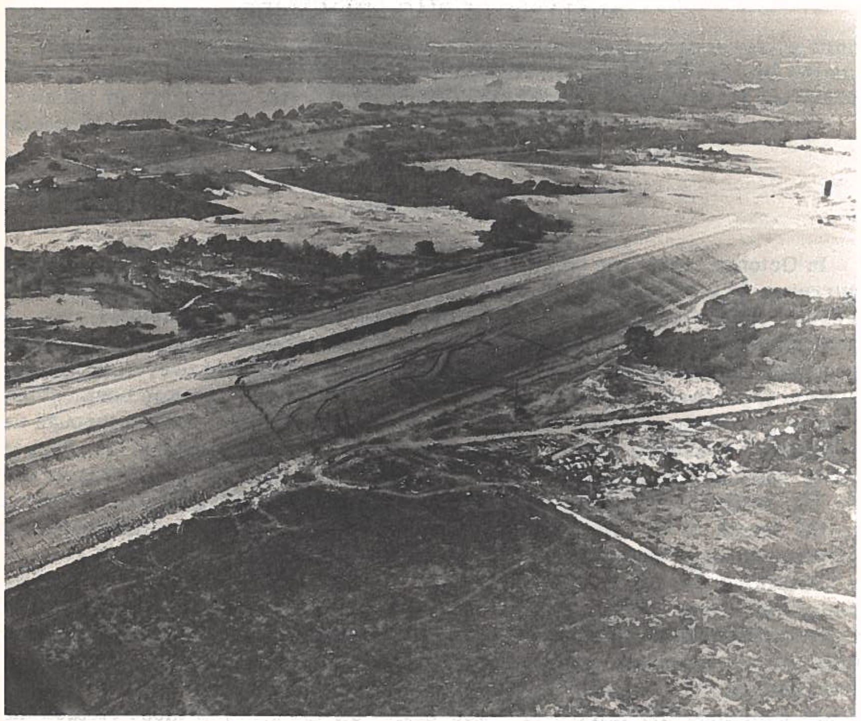

FIG. 1.—WACO DAM SLIDE

high degree of closely spaced, horizontal fissuring. A recent review by Skempton and Hutchinson (5) has shown that a number of factors may influence the undrained strength of such stiff-fissured clays as the Pepper shale. These factors include anisotropy, specimen size, creep strength loss due to sustained loading, and progressive failure due to high peak to residual strength ratios. In order to determine the influence of these factors on the undrained shear strength of Pepper shale, a comprehensive series of tests was conducted.

To study the effects of anisotropy, unconsolidated-undrained triaxial compression tests were performed on inclined specimens using procedures

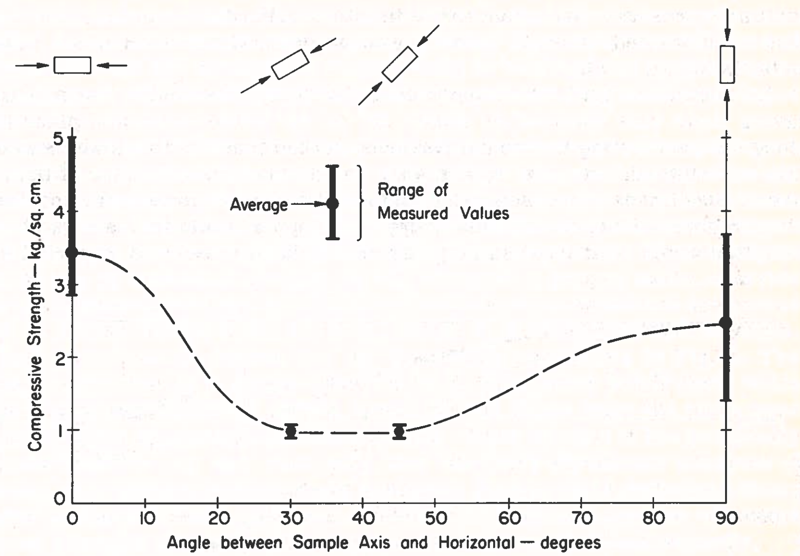

FIG. 2.—VARIATION IN UNDRAINED STRENGTH WITH SAMPLE ORIENTATION FOR PEPPER SHALE

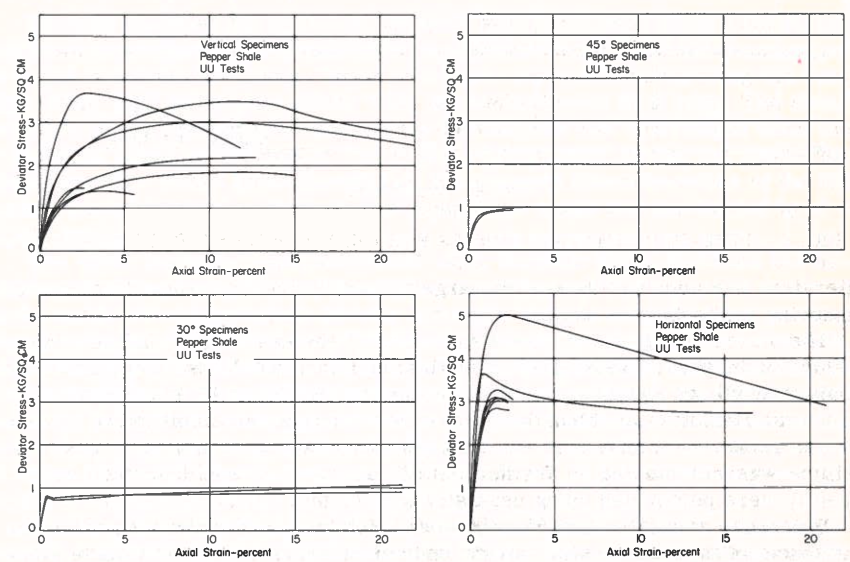

FIG. 3.—STRESS-STRAIN CURVES FOR PEPPER SHALE

similar to those employed by Ward, Samuels, and Butler (6). Specimens were trimmed with these axes at several orientations and were tested using a confining pressure equivalent to the in situ overburden pressure. The variation of undrained strength with speciment orientation, determined in these tests, is shown in Fig. 2.

As shown in Fig. 2, the Pepper shale is highly anistropic. The specimens having their axis inclined at either 30° or 45° to the horizontal plane failed along the preexisting horizontal fissures and had considerably lower strengths than conventional vertical specimens. In addition, the strengths of the horizontal specimens were somewhat higher than those of vertical specimens. The pronounced degree of anisotropy for Pepper shale indicates a strength variation which is at least as large as any of those previously reported in the

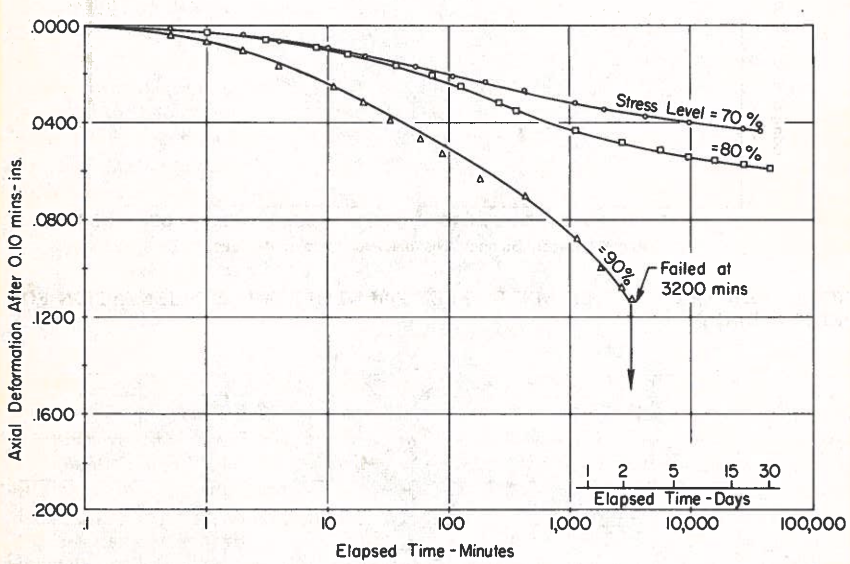

FIG. 4.—TIME-DEFORMATION CURVES FOR CREEP TESTS ON PEPPER SHALE

literature and undoubtedly results largely from the predominance of horizontal fissuring in the Pepper shale.

The stress-strain curves for Pepper shale, shown in Fig. 3, indicate some reduction in shear resistance of vertical and horizontal specimens after the peak strength is reached, but none in the case of 30° or 45° specimens. Because the reduction in strength appears to be of negligible significance in view of the amount of scatter in the strength data, the possibility of progressive failure was not studied in further detail, and the analyses described subsequently were performed using peak strength values.

Peterson, et al. (4) and Skempton and Hutchinson (5) have shown that the influence of specimen size on the undrained shear strength of some stiff-fissured clays and shales is quite large. Peterson reported that the strength of 6-in. diam specimens of Bearpaw shale was only about one-sixth as large as the strength of 1.4-in. diam specimens. To investigate the influence of

specimen size on the undrained strength of Pepper shale, tests were performed on vertical and horizontal specimens of three different sizes, ranging from 1.4-in. diam to 4-in. diam. The results of these tests indicated no noticeable variation in shear strength with specimen size. The negligible influence of specimen size on the strength of Pepper shale is believed to result from the uniform degree of fissuring in all specimens and the very close spacing of the fissures.

Casagrande and Wilson (2) have shown that the strength of heavily over-consolidated, stiff-fissured clays and clay shales also may be significantly influenced by the effect of sustained loading. Some specimens of the Cucaracha shale from the Panama Canal failed after 15 days of sustained loading at stress levels as low as about 20 % of the short-term strength. To investigate the influence of sustained loading on the strength of Pepper shale, a series of unconsolidated-undrained triaxial creep tests was performed on specimens loaded to stress levels of 70 %, 80 %, and 90 % of the short-term strength. The time-deformation curves for all specimens are shown in Fig. 4. The specimen subjected to a stress level of 90 % failed after 2-1/2 days, while the specimens at the lower stress levels had not failed when the tests were terminated after 30 days of sustained loading. Thus, in view of the previously mentioned scatter in the test data and the very significant influence of anistropy, the relative importance of sustained loading on the undrained shear strength of Pepper shale appeared relatively insignificant, and no allowance for creep strength loss was made in the analyses described subsequently.

STABILITY ANALYSES

Stability analyses for the Waco Dam slide were performed using total stress analysis procedures and strength values measured in unconsolidated-undrained triaxial compression tests. These analyses were performed using the configuration just before the slide, with the embankment 85 ft high. The shear strength of the fill material employed in the analyses was determined from the results of tests performed by the Corps of Engineers during the post-slide investigation. These tests showed that the strength characteristics of the fill under unconsolidated-undrained test conditions could be represented by C = 1,800 psf, and $\phi = 0$.

The first analyses were performed using circular shear surfaces and assuming that the strength of the Waco Dam foundation was isotropic and uniform, and could be represented by the strength values measured for vertical specimens of Pepper shale. The most critical circle for these analyses, shown in Fig. 5, was found to have a factor of safety of 1.32. This result thus seems to indicate an acceptable margin of safety, even though the embankment actually failed at the stage represented in the analyses. Furthermore, the post-slide exploration program showed that the actual shear surface, which is also shown in Fig. 5, was considerably flatter and extended only to mid-depth of the Pepper shale.

Additional analyses of the Waco Dam slide were performed using anisotropic shear strengths for the Pepper shale. The strength values used in these analyses were determined using the average strength values for each of the orientations shown in Fig. 2, assuming that the failure plane was inclined at 30° to the axis of the specimen. Assuming that the strength was

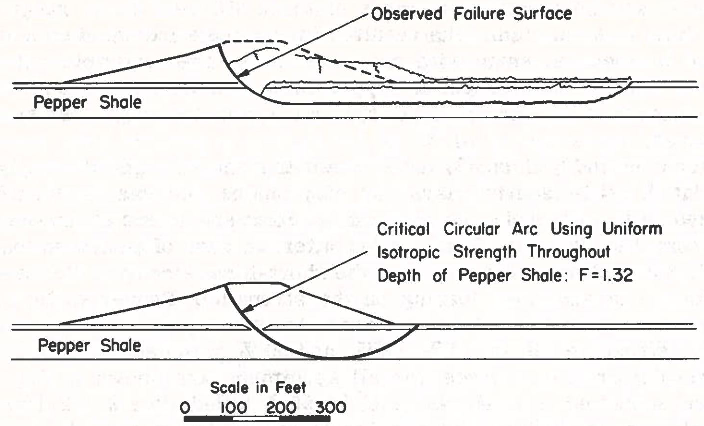

FIG. 5.—FAILURE SURFACES FOR WACO DAM

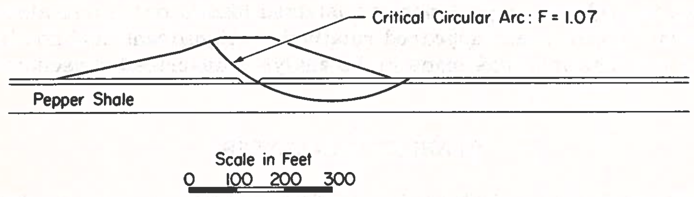

FIG. 6.—ANALYSIS USING UNIFORM ANISOTROPIC STRENGTHS THROUGHOUT DEPTH OF PEPPER SHALE

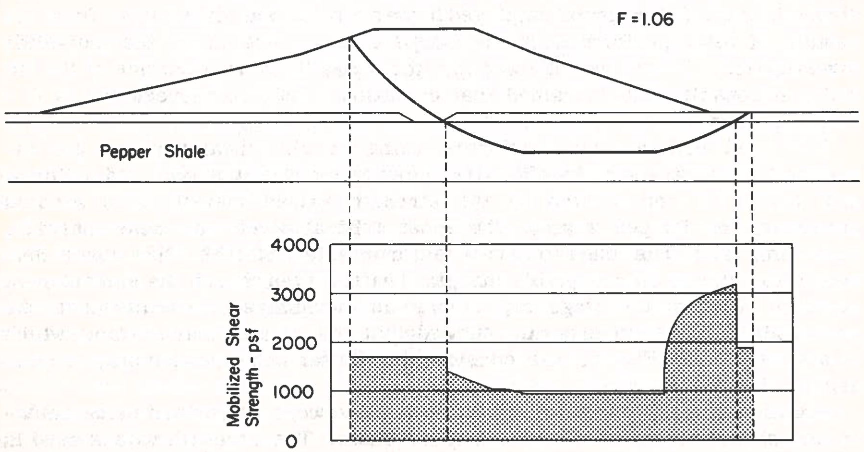

FIG. 7.—MOBILIZED SHEAR STRENGTH ALONG SHEAR SURFACE

uniform throughout the depth of the Pepper shale, the computed factor of safety for the most critical circular arc was 1.07. Thus, considering the anisotropic shear strength of the Pepper shale, the factor of safety was found

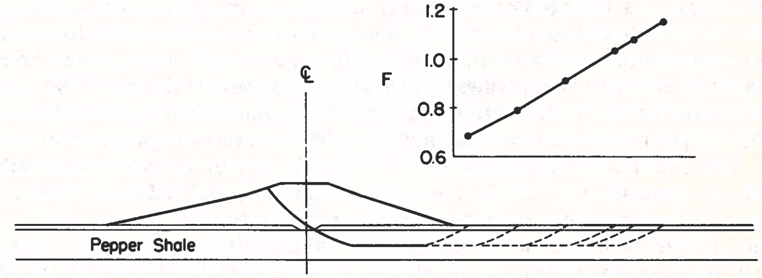

FIG. 8.—INFLUENCE OF EXTENSION OF FAILURE SURFACE DOWNSTREAM TO ASSUMED WEAK ZONE

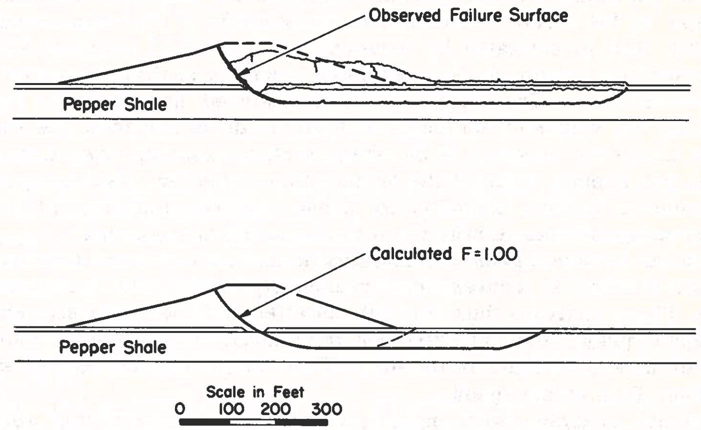

FIG. 9.—ANALYSIS WITH REDUCED SHEAR STRENGTH DOWNSTREAM

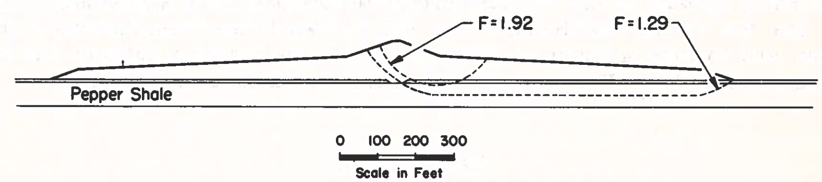

FIG. 10.—ANALYSES OF RECONSTRUCTED SECTION OF WACO DAM

to be considerably lower, and in much better agreement with the occurence of the slide. For practical purposes, considering the amount of scatter in the strength data, a calculated value of the factor of safety equal to 1.07 is considered to be consistent with the fact that failure did occur. The critical circle for these analyses did not pass to the bottom of the Pepper shale as did the critical circle for the previous analyses with isotropic strengths. Instead, as shown in Fig. 6, the critical circle passed to only about two-thirds the depth of the Pepper shale, indicating that the location of the potential failure surface is changed considerably when anisotropy is considered.

In order to study the stability for noncircular surfaces, the critical circle found using anisotropic strengths was flattened to form a noncircular surface passing horizontally at mid-depth through the Pepper shale, as shown in Fig. 7. The factor of safety for this surface was calculated using the Morgenstern and Price (3) procedure with a uniform side force assumption, $f(x)$ = constant. The results of this analysis showed that the factor of safety was reduced to 1.06, as compared to 1.07 for the circular surface, and indicated that a noncircular failure surface would be slightly more critical.

The analyses which were performed using anisotropic shear strengths showed that a large portion of the shear resistance mobilized along the shear surface was derived from a relative small portion of the surface near the toe of the embankment, as shown in the lower portion of Fig. 7. If, as Beene suggested, a weaker zone in the Pepper shale existed downstream from the toe of the embankment, its presence might have a considerable influence on the shape of the failure surface and the stability of the embankment. This possibility was investigated by performing a series of analyses similar to those described previously, but assuming a zone of negligible passive resistance downstream. The shear surfaces analyzed are shown in Fig. 8. In calculating the values of the factor of safety of these surfaces, the shear resistance along the portions of the shear surfaces passing upward from mid-depth of the Pepper shale to the surface was neglected. As shown in Fig. 8, the calculated factors of safety for these surfaces were found to increase with increasing distance downstream to the assumed weak zone.

The shear surface having a calculated factor of safety equal to unity, which is shown in Fig. 9, corresponds reasonably well to the observed failure surface. These analyses thus illustrate the effect of a low shear strength along a horizontal plane, and the existence of an apparently weakened zone downstream in the Pepper shale, on the shape of the failure surface and the stability of the Waco Dam embankment.

Additional analyses were performed for the reconstructed section of Waco Dam. The results of these analyses are shown in Fig. 10. The critical shear surface, analyzed neglecting the shear resistance along the portion extending upward to the surface through the Pepper shale, was found to exit at the toe of the stabilizing berm, 880 ft downstream from the axis of the dam, and to have a factor of safety of 1.29. These analyses indicate that the reconstructed Waco Dam embankment should be stable, as in fact it is.

CONCLUSIONS

This investigation showed that the undrained shear strength of Pepper shale is highly anisotropic. The strength along a horizontal plane was found to be only about 40 % as large as the strength measured in conventional unconsolidated-undrained compression tests on vertical specimens. While total stress analyses based on isotropic strengths from vertical specimens of Pepper shale indicated stable conditions at the time of the Waco Dam slide, the use of anisotropic strengths produced results in agreement with the observed failure, and with the development of a pronounced noncircular failure surface.

The significant influence of the anisotropy of Pepper shale on the failure of Waco Dam shows the importance of considering anisotropy in analyses for the stability of embankments founded on heavily overconsolidated, stiff-fissured clays and clay shales. In addition to anisotropy, several other factors, including specimen size and rate of loading, are known to influence the strength of stiff-fissured clays and clay shales, and their effects should also be considered in investigations of embankment stability on stiff-fissured clays and clay shales.

ACKNOWLEDGMENT

The writers express their appreciation to the National Science Foundation which provided financial support for this study, and to the U.S. Army Corps of Engineers' Fort Worth District Office and Southwestern Division Laboratory for supplying information and soil samples used herein.

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