CHAPTER 1

Introduction

Evaluating the stability of slopes in soil is an important, interesting, and challenging aspect of civil engineering. Concerns with slope stability have driven some of the most important advances in our understanding of the complex behavior of soils. Extensive engineering and research studies performed over the past 70 years provide a sound set of soil mechanics principles with which to attack practical problems of slope stability.

Over the past decades, experience with the behavior of slopes, and often with their failure, has led to development of improved understanding of the changes in soil properties that can occur over time, recognition of the requirements and the limitations of laboratory and in situ testing for evaluating soil strengths, development of new and more effective types of instrumentation to observe the behavior of slopes, improved understanding of the principles of soil mechanics that connect soil behavior to slope stability, and improved analytical procedures augmented by extensive examination of the mechanics of slope stability analyses, detailed comparisons with field behavior, and use of computers to perform thorough analyses. Through these advances, the art of slope stability evaluation has entered a more mature phase, where experience and judgment, which continue to be of prime importance, have been combined with improved understanding and rational methods to improve the level of confidence that is achievable through systematic observation, testing, and analysis. This seems an appropriate stage in the development of the state of the art to summarize some of these experiences and advances in a form that will be useful for students learning about the subject and for geotechnical engineers putting these techniques into practice. This is the objective that this book seeks to fill.

Despite the advances that have been made, evaluating the stability of slopes remains a challenge. Even when geology and soil conditions have been evaluated in keeping with the standards of good practice, and stability has been evaluated using procedures that have been effective in previous projects, it is possible that surprises are in store. As an example, consider the case of the Waco Dam embankment.

In October 1961, the construction of Waco Dam was interrupted by the occurrence of a slide along a 1500-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 Figure 1.1. 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.

The section of the embankment involved in the slide 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 and to develop a method for repairing the slide. The investigation showed that the slide extended for several hundred feet downstream from the embankment, within the Pepper shale foundation. A surprising finding of the studies conducted after the failure was the highly anisotropic nature of the Pepper shale, which contained pervasive horizontal slickensided fissures spaced about $\frac{1}{8}$ in. (3 mm) apart. The strength along horizontal planes was found to be only about 40% as large as the strength measured in conventional tests on vertical specimens. Although conventional testing and analysis indicated that the embankment would be stable throughout construction, analyses performed using the lower strengths on horizontal planes

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Figure 1.1 Slide in the downstream slope of the Waco Dam embankment.

produced results that were in agreement with the failure observed (Wright and Duncan, 1972).

This experience shows that the conventional practice of testing only vertical samples can be misleading, particularly for stiff fissured clays with a single dominant fissure orientation. With the lesson of the Waco Dam experience in mind, geotechnical engineers are better prepared to avoid similar pitfalls.

The procedures we use to measure soil strengths and evaluate the stability of slopes are for the most part rational and may appear to be rooted solidly in engineering science. The fact that they have a profound empirical basis is illustrated by the case of an underwater slope in San Francisco Bay. In August 1970, during construction of a new shipping terminal at the Port of San Francisco, a 250-ft (75-m)-long portion of an underwater slope about 90 ft (30 m) high failed, with the soil on one side sliding into the trench, as shown in Figure 1.2. The failure took place entirely within the San Francisco Bay mud, a much-studied highly plastic marine clay.

Considerable experience in the San Francisco Bay area had led to the widely followed practice of excavating underwater slopes in Bay mud at 1 (horizontal):1 (vertical). At this new shipping terminal, however, it was desired to make the slopes steeper, if possible, to reduce the volume of cut and fill and the cost of the project. Thorough investigations, testing, and analyses were undertaken to study this question.

Laboratory tests on the best obtainable samples, and extensive analyses of stability, led to the conclusion that it would be possible to excavate the slopes at 0.875:1. At this inclination, the factor of safety computed for the slopes would be 1.17. Although such a low factor of safety was certainly unusual, the conditions involved were judged to be exceptionally well known and understood, and the slopes were excavated at the steep angle. The result was the failure depicted in Figure 1.2. An investigation after the failure led to the conclusion that the strength of the Bay mud that could be mobilized in the field over a period of several weeks was lower than the strength measured in laboratory tests in which the Bay mud was loaded to failure in a few minutes, and that the cause of the difference was creep strength loss (Duncan and Buchignani, 1973).

The lesson to be derived from this experience is that our methods may not be as scientifically well founded as they sometimes appear. If we alter our conventional methods by ''improving'' one aspect, such as the quality of samples used to measure the undrained strength of Bay mud, we do not necessarily achieve a more accurate result. In the case of excavated slopes in Bay mud, conventional sample quality and conventional test procedures, combined with conventional values of factor of safety, had been successful many times. When the procedures were changed by ''refining'' the sampling and strength testing procedures, the result was higher values of undrained shear strength than would have been measured if conventional procedures had been used. When, in addition, the value of the safety factor was reduced, the result was a decision to use an

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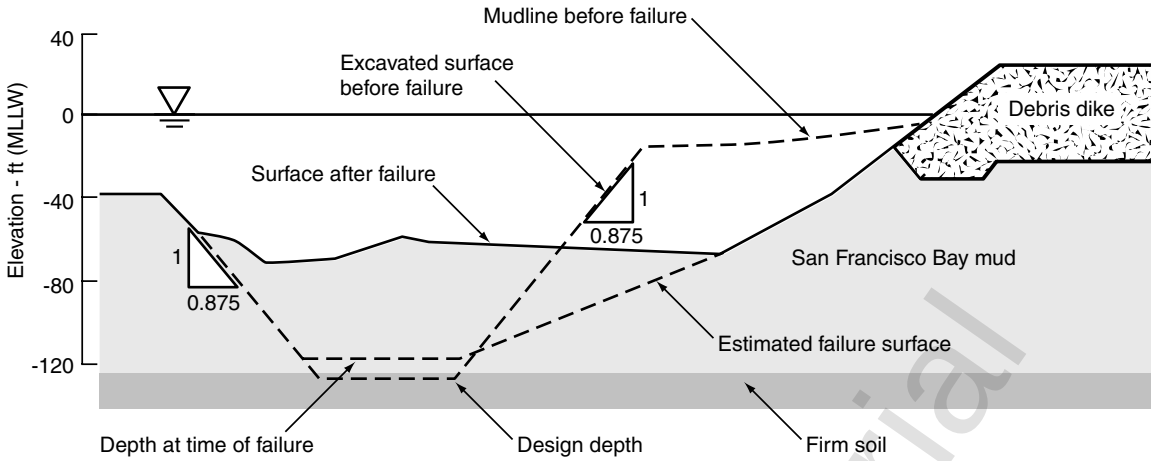


Figure 1.2 Failure of the San Francisco LASH Terminal trench slope.

excessively steep slope, which failed. Altering conventional practice and reducing the factor of safety led to use of a procedure that was not supported by experience.

SUMMARY

The broader messages from these and similar cases are clear:

1. We learn our most important lessons from experience, often from experience involving failures. The state of the art is advanced through these failures and the lessons they teach. As a result, the methods we use depend strongly on experience. Despite the fact that our methods may have a logical background in mechanics and our understanding of the behavior of soils and rocks, it is important to remember that these methods are semi-empirical. We depend as much on the fact that the methods have worked in the past as we do on their logical basis. We cannot count on improving these methods by altering only one part of the process that we use.
2. We should not expect that we have no more lessons to learn. As conditions arise that are different from the conditions on which our experience is based, even in ways that may at first seem subtle, we may find that our semi-empirical methods are inadequate and need to be changed or expanded. The slide in Waco Dam served clear notice that conventional methods were not sufficient for evaluating the shear strength of Pepper shale and the stability of embankments founded on it. The lesson learned from that experience is now part of the state of the art, but it would be imprudent to think that the current state of knowledge is complete. We need to keep abreast of advances in the state of the art as they develop and practice our profession with humility, in recognition that the next lesson to be learned may be lurking in tomorrow's project.

The objective of this book is to draw together some of the lessons that have been learned about measuring soil strengths and performing limit equilibrium analyses of stability into a consistent, clear, and convenient reference for students and practicing engineers.

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