Parametric effects on slope stability analysis

by Robert Lorin Sanderson

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
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Abstract:
The purpose of this investigation was to determine the relative effect of soil parameter and failure surface variance on the factor of safety against sliding in two selected heterogeneous finite slopes. Two actual finite slope cross-sections taken from Montana Highway Commission files were used in the study. One section was a typical highway fill placed on a multilayered subbase. The other was a typical cut section through gently dipping bedded material overlain by a considerable depth of alluvium.

The method of analysis used was a series of digital computer solutions based on the "method of slices." The method of slices was adapted for use on a combination circular and planar failure surface for analysis of the cut section stability. For both trial problems, soil parameters, soil boundaries, and failure surfaces were systematically changed in order that the effect of these variables on slope stability could be observed.

The results of the investigation revealed that certain patterns of failure arc locations can be expected for specific soil conditions.

Changes in any one soil property, i.e., unit cohesion, unit weight, or internal friction angle, will result in a change in the failure arc location and thus a change in the relative stability. It was determined that the use of a fixed or "best guess" failure arc can be used with a high degree of accuracy if the arc position is within the characteristic failure pattern of the cross-section. If the fixed arc is not representative of the typical failure condition, an equally high degree of inaccuracy results.

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Signature Robert Lorin Anderson Jr.

Date November 24, 1969

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TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

ABSTRACT

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CHAPTER I

INTRODUCTION

Approach to Stability Analysis

Men of scientific interest and background have been studying the problems of the stability of earth slopes for many years. At first, theory behind movement of soil and rock was essentially undeveloped and men relied on experience and sound judgment in analyzing stability problems. Gradually as the theory was advanced, more and more of a gap formed between quantitative and qualitative methods of slope stability analysis. Geologists continued to rely on actual field conditions and the geologic history of an area as a basis for final conclusions. Engineers have followed closely the development of quantitative slope stability theory based on the fundamentals of mechanics and the use of various theoretical methods has become widespread.

Many different quantitative approaches to the problem of determining the stability of slopes are presently in use. Definite limitations to the application of the quantitative approach exist and must be recognized by the engineer. Basically, all quantitative methods assume failure occurs on either a circular or planar surface. While these two basic approaches can be applied with varying degrees of accuracy to many actual slope stability problems, it needs to be recognized that a great many situations exist that do not lend themselves to straight-forward quantitative analysis. In many cases, the particular geologic structure in the unstable area is such that a definite failure arc or failure plane cannot rationally be predicted. Such problems must then be analyzed using basic geologic considerations.

Quantitative Analysis Limitations

The fact that the numerous quantitative methods have limitations, as far as general application to slope stability problems is concerned, is well-known and well-documented in the literature. Terzaghi and Peck (1948) made a brief statement concerning those limitations as follows:

> Because of the extraordinary variety of factors and processes that may lead to slides, the conditions for the stability of slopes usually defy theoretical analysis. Stability computations based on test results can be relied on only when conditions specified (in each method of analysis) are strictly satisfied. Moreover, it should always be remembered that various undetected discontinuities of sliding, or thin seams of water-bearing sand, may completely invalidate the results of computations.

Eckel (1958) covers the subject of mathematical stability analyses limitations as well as any of the literature searched. Eckel states in part that " . . . the analyses cannot be made for every type of landslide and for any type a number of assumptions based on idealized conditions and materials will be required. It is impossible to treat mathematically all of the variables imposed by nature."

If mathematical approaches to slope stability analysis have limitations, and these limitations are known, of what use are the results of such analyses? It is easy to see how quantitative estimates of the magnitude of forces involved in a sliding mass would aid in designing adequate corrective measures. Also, the knowledge of these forces and their magnitudes determined from an existing slide, may be applied to the prediction of sliding in an adjacent area of similar geologic structure. The economic feasibility of maintaining or correcting unstable slopes is usually based on analytical stability analysis.

Factor of Safety Against Sliding

Most quantitative methods of stability analysis give a factor of safety against sliding as the end result. Although factors of safety may be calculated in many different ways, the quotient of resisting and activating forces along the potential failure surface is most commonly used. The value of the factor of safety is only as good as the assumptions made in applying a particular analysis. The factor of safety is a good indicator of relative stability, however, and is often used in this manner.

Data Required for Analysis

Obtaining the precise information required to apply a quantitative slope stability analysis is not ordinarily a straight-forward accumulation of data. First, and possibly most important, the general geology of the existing or potential slide area must be known. The engineer must know the properties of the materials contained in the slope. These properties include the strength parameters, unit cohesion and angle of internal friction, and the soil unit weight. An adequate drilling, sampling, and laboratory testing program must be formulated at this stage of the investigation in order to obtain the above information.

Before continuing with the above mentioned procedures, however, the engineer must decide how thorough an investigation is warranted or necessary. With unlimited finances, time, and equipment, it is possible to accurately determine conditions of slope stability where quantitative methods of analysis are applicable. Precise determination of the soil parameters mentioned above, for instance, is time consuming and costly. Most often, however, representative samples are taken from drill holes, soil parameters are averaged, and factors of safety against sliding are calculated along assumed representative failure arcs. It is known that in any given embankment a certain combination of possible values of soil parameters, slope, and slope height, along with a particular failure arc location, will give a minimum factor of safety against sliding. Because of the usual case of limited time and funds, however, only representative cases based on experience are evaluated, and the true minimum condition is not necessarily determined.

Need for Investigation

There is a definite need for information regarding the seriousness of not knowing the conditions of the most critical sliding situation. One way of developing this data is to determine the sensitivity of the factor of safety against sliding to minor change in each of the soil parameters and the position of the failure arc. With a knowledge of the effect of each of these changes on the accuracy of quantitative slope stability analyses, the engineer should do a better job of determining how extensive a field and laboratory investigation need be in a specific case.

Previous work in isolating the effect of individual parameters has been varied and incomplete. Taylor (1948) described one method of illustrating the effect by defining what he called a stability number. The stability number is:

$$\frac{cD}{\gamma H}$$

where: cD = the mobilized cohesion in pounds per square foot

γ = soil unit weight in pounds per cubic foot, and

H = slope height in feet.

Taylor's results show the relationship between stability number and slope angle for various angles of internal friction. The relationships are shown for simple, homogeneous, finite slopes with fixed failure arc positions. Relative stability of more complex slopes could only be approximated from the use of these relationships.

In the usual slope stability problem confronting the engineer, the slope geometry is a function of the soil characteristics. In a highway design situation, a cut or fill slope angle is proposed or desired, and the height of the existing or proposed slope has been determined from requirements of grade. Therefore, the most difficult task is to determine the soil parameters and then determine, in turn, the position of the critical failure surface.

Purpose of Investigation

The primary objective of this study was to investigate the effect of soil parameter and failure surface variance on the relative stability of two selected heterogeneous finite slopes. Two typical slope stability problems, a highway cut section and a highway fill section, were used in this investigation. Stability analyses were conducted on these slopes to determine minimum factors of safety against sliding for selected combinations of soil parameters and failure arc positions. From the results of these computations, an analysis was made of the effect of using average or approximate values of the soil parameters and approximate positions of the critical failure surface.

CHAPTER II

DEFINITIONS OF TERMINOLOGY AND REVIEW OF SLOPE FAILURE CONDITIONS

Finite Slope Description

The basic finite slope configuration is shown in Figure 1. As shown in the figure, more than one soil type may be represented in the typical cross-section. The slope itself may be at any angle, and the ground surface above and below the slope may or may not be horizontal. For the purposes of discussion in this study, all cross-sections will be represented by the basic (x,y) coordinate system as shown in Figure 1.

Soil Characteristics

Three basic properties describe each soil included in a slope stability problem. They are the soil unit weight, soil unit cohesion, and the angle of internal friction. The soil unit weight, γ, is defined as the total weight of the soil per unit volume.

The two remaining properties, unit cohesion and internal friction, are directly responsible for the shearing strength of a particular soil and thus are very important in all slope stability calculations. Shearing strength has been defined by Spangler (1963) as "the property which enables soil to maintain equilibrium on a sloping surface, such as a natural hillside, the backslope of a highway or railway cut, or the sloping sides of an embankment, levee, or earth dam."

Mass-Movement Classification

In a typical finite slope situation, such as that shown in Figure 1, several different types of failure can take place. Classification of various landslide and mass-movement types is well-covered in the literature. The most thorough geological classification is that of Sharpe (1938).

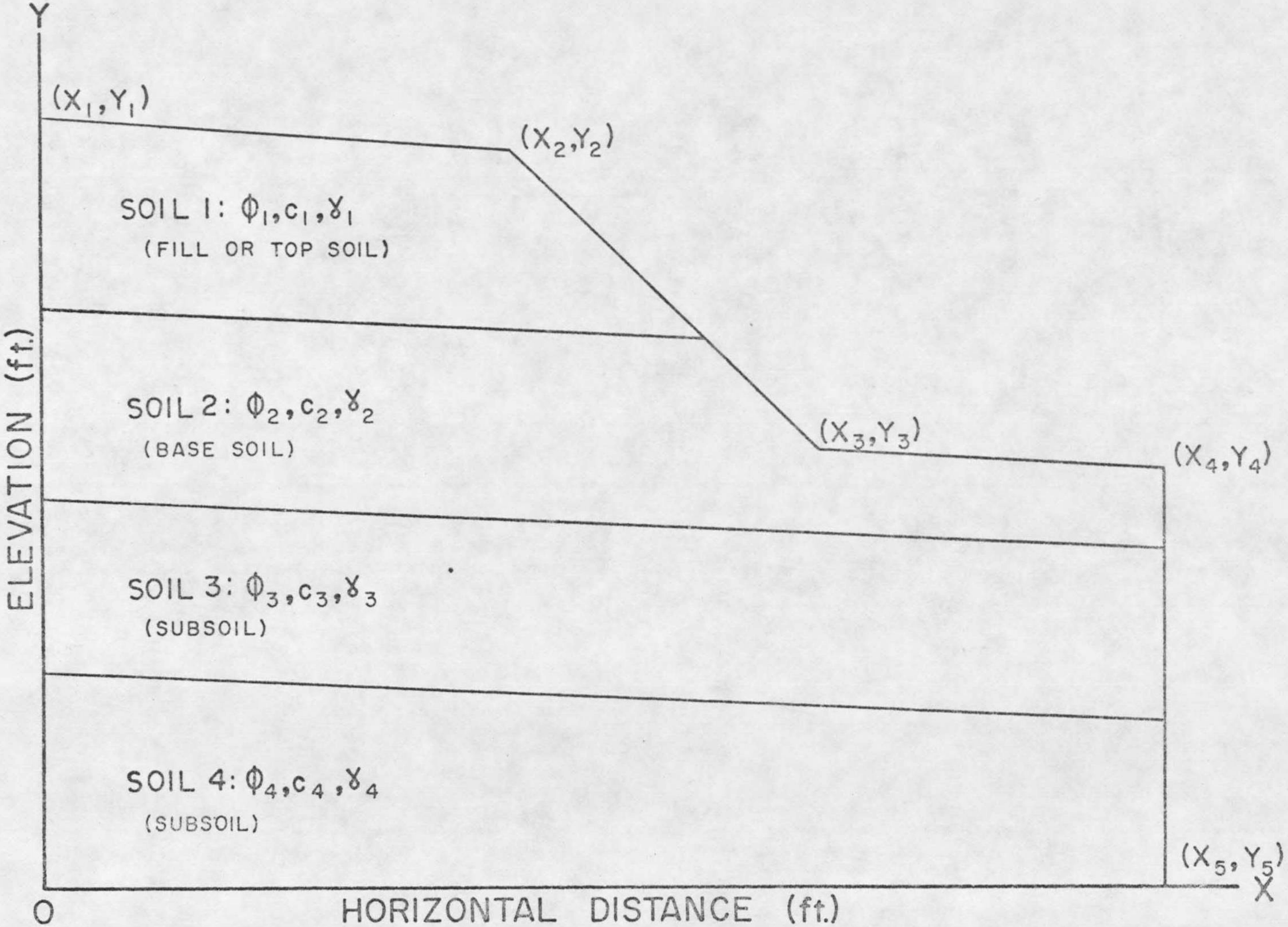

Figure 1. Basic configuration of heterogeneous finite slope.

Sharpe classified mass-movement into two distinct categories; that of slides and flows. He noted one basic distinction between the two types of movement. If a slope or shear plane separates the moving mass from the stable ground, the movement is termed a slide. If no distinct slip plane exists, the movement is plastic or viscous and has occurred due to continuous deformation of the material involved. The latter type of movement is classed as a flow. These distinctions must be qualified, however, because cases seldom exist where only "slippage" or "flowage" occurs. Some cases of flowage may actually start as slippage and vice-versa.

Basically, then, Sharpe (1938) divided all forms of mass-movement into four groups, and each group into subgroups:

1. Slow flowage
   a. Rock-creep
   b. Talus-creep
   c. Soil-creep
   d. Rock-glacier creep
   e. Solifluction
2. Rapid flowage
   a. Earthflow
   b. Mudflow
   c. Debris-avalanches
3. Sliding
   a. Slump
   b. Debris-slide
   c. Debris-fall
   d. Rockslide
   e. Rockfall
4. Subsidence

Of these four categories, only the third contains types of failures in which an actual shear surface could be defined. Of these types of failure, only that of slump, debris-slide, and rockslide occur on a shear surface. Those of debris-fall and rockfall are of a free-falling nature, and a sliding surface, as such, cannot be defined.

Quantitative Analysis Application

From the above discussion, it can be seen that the mathematical principles are limited in application to but a few cases in the overall mass-movement classification. That the other categories do exist and are a common threat to man-made structures is well-known. It is thus important that a complete perspective of the sliding or mass-movement possibilities is recognized and the analytical analysis, therefore, has limitations.

In summary, the types of slope failure most often analyzed analytically are slump, debris-slide, and rockslide. As defined by Sharpe (1938), the slump is " . . . the downward slipping of a mass of rock or unconsolidated material of any size, moving as a unit or as several subsidary units, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope from which it descends." The slump type of slide has a definite shear surface which is usually partially, and quite often wholly, arc-shaped.

The debris-slide is defined by Sharpe as a " . . . rapid downward movement of predominantly unconsolidated and incoherent earth and debris in which the mass does not show backward rotation but slides or rolls forward, forming an irregular hummocky deposit which may resemble morainal topography. Debris-slides are very common and are usually quite small. They occur on most talus slopes or any other slope which is steep enough that a minor disturbance may cause sliding of unconsolidated material. A definite sliding plane is often difficult to determine as the material moves in a rolling or tumbling manner.

The third shear surface type of slide according to Sharpe's system is a rockslide. He defines a rockslide as " . . . the downward and usually rapid movement of newly detached segments of the bedrock sliding on bedding, joint, or fault surfaces or any other plane of separation." Rockslides are not as common as slumps or debris-slides; however, several of the more destructive slope failures in history have been rockslides.

Planar block glide is a type of slide which is similar to the rockslide except that the planar block acts more as a single unit. The planar block glide category was introduced in a classification system developed by the Committee on Landslide Investigations of the Highway Research Board as reported by Eckel (1958). The classification system parallels Sharpe's rather closely, although several cause and effect relationships introduced are engineering oriented. One important difference in the methods of classification is the addition of the planar block glide category.

Eckel indicates that the planar block glide type of slide is actually quite common, but it has received very little coverage in the literature. Eckel describes the block glide as a mass progressing " . . . out, or down and out, as a unit along a more or less planar surface, without the rotary movement and backward tilting characteristic of slump." Eckel points out that the important difference between slump and block glide is revealed in the type of control that is necessary to prevent sliding from occurring or continuing to occur. As a slumping mass rotates along its failure arc, energy is gradually dissipated and the slide comes to a rest. A block glide, in contrast, will continue to slide indefinitely as long as the sliding surface remains inclined and a low value of shearing resistance exists. Control, then, may be a much greater problem with the block glide situation.

Quantitative Slope Stability Analysis

Many analytical approaches to stability analysis have been developed with regard to both planar and curved surfaces. Planar surface analyses simply involve the basic theory of a soil mass sliding on an inclined plane. The situation can be likened to Sharpe's rockslide definition, as a definite sliding surface is apparent. Also, block glide or block slide as discussed previously fits the planar sliding surface type of analysis.

Probably the most popular and most widely used method of analyzing failures on a curved surface is the method of slices. Eckel (1958) reports that this method was developed by W. Fellenius in 1926. Many variations of the basic method of slices have been developed and are in use. Also, many other mathematical solutions for slope failure along arc-shaped surfaces have been successfully applied. All use the same soil mechanics principles, however, and a brief explanation of the simplified method of slices will serve to illustrate the nature of these solutions.

Figure 2 shows the typical geometric cross-section of an arc-shaped failure surface on a finite slope.

The method of slices can be solved analytically or graphically and has been successfully adapted to digital computer programs. As