Stability Modeling with

SLOPE/W 2007 Version

An Engineering Methodology

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1 Introduction

Analyzing the stability of earth structures is the oldest type of numerical analysis in geotechnical engineering. The idea of discretizing a potential sliding mass into slices was introduced early in the 20th Century. In 1916, Petterson (1955) presented the stability analysis of the Stigberg Quay in Gothenberg, Sweden where the slip surface was taken to be circular and the sliding mass was divided into slices. During the next few decades, Fellenius (1936) introduced the Ordinary or Swedish method of slices. In the mid-1950s Janbu (1954) and Bishop (1955) developed advances in the method. The advent of electronic computers in the 1960's made it possible to more readily handle the iterative procedures inherent in the method which led to mathematically more rigorous formulations such as those developed by Morgenstern and Price (1965) and by Spencer (1967). One of the reasons the limit equilibrium method was adopted so readily, is that solutions could be obtained by hand-calculations. Simplifying assumption had to be adopted to obtain solutions, but the concept of numerically dividing a larger body into smaller pieces for analysis purposes was rather novel at the time.

Even to this day, stability analyses are by far the most common type of numerical analysis in geotechnical engineering. This is in part because stability is obviously a key issue in any project – will the structure remain stable or collapse? This, however, is not the only reason. Concepts associated with the method of slices are not difficult to grasp and the techniques are rather easy to implement in computer software – the simpler methods can even be done on a spreadsheet. Consequently, slope stability software became available soon after the advent of computers. The introduction of powerful desktop personal computers in the early 1980s made it economically viable to develop commercial software products based on these techniques, and the ready availability today of such software products has led to the routine use of limit equilibrium stability analysis in geotechnical engineering practice.

Modern limit equilibrium software is making it possible to handle ever-increasing complexity within an analysis. It is now possible to deal with complex stratigraphy, highly irregular pore-water pressure conditions, various linear and nonlinear shear strength models, almost any kind of slip surface shape, concentrated loads, and structural reinforcement. Limit equilibrium formulations based on the method of slices are also being applied more and more to the stability analysis of structures such as tie-back walls, nail or fabric reinforced slopes, and even the sliding stability of structures subjected to high horizontal loading arising, for example, from ice flows.

While modern software is making it possible to analyze ever-increasingly complex problems, the same tools are also making it possible to better understand the limit equilibrium method itself. Computer-assisted graphical viewing of data used in the calculations makes it possible to look beyond the factor of safety. For example, graphically viewing all the detailed forces on each slice in the potential sliding mass, or viewing the distribution of a variety of parameters along the slip surface, helps greatly to understand the details of the technique.

While the graphical viewing of computed details has led to a greater understanding of the method, particularly the differences between the various methods available, it has also led to the exposure of limitations in the limit equilibrium formulations. Exposure of the limitations has revealed that the method is perhaps being pushed too far beyond its initial intended purpose. The method of slices was initially conceived for the situation where the normal stress along the slip surface is primarily influenced by gravity (weight of the slice). Including reinforcement in the analysis goes far beyond the initial intention. Even though the limitations do not necessarily prevent using the method in practice, understanding the limitations is vital to understanding and relying on the results.

Despite the extensive and routine use of stability analyses in practice, it seems the fundamentals of the limit equilibrium method of slices are not well understood. The fact that the limit equilibrium method of slices is based on nothing more than statics often seems to be forgotten, and the significance of one factor of safety for all slices is not appreciated.

SLOPE/W, in one form, or another has been on the market since 1977. The initial code was developed by Professor D.G. Fredlund at the University of Saskatchewan. The first commercial version was installed on mainframe computers and users could access the software through software bureaus. Then in the 1980s when Personal Computers (PCs) became available, the code was completely re-written for the PC environment. Processing time was now available at the relatively low fixed cost of the computer, but computer memory was scarce and so the code had to be re-structured for this hardware environment. The product was renamed PC-SLOPE and released in 1983. Later in the 1980s it became evident that graphical interaction with PC software was going to be the wave of the future, and consequently a graphical CAD-like user interface was developed. The software was again renamed as SLOPE/W to reflect the Microsoft Windows environment and that it now had a graphical user interface. SLOPE/W was the very first geotechnical software product available commercially for analyzing slope stability. Currently, SLOPE/W is being used by thousands of professionals both in education and in practice.

Over the years, as computer technology has advanced, SLOPE/W has continually been enhanced and upgraded. This book is based on Version 7 of the program.

When using software like SLOPE/W with its myriad of options, it is often necessary to look at more than just the factor of safety. Other issues to consider include, but are not limited to: Was the intended data correctly specified? Was the data used correctly by the software? Why are there differences between factors of safety from the various methods? To help answer these types of questions, SLOPE/W has many tools for inspecting the input data and evaluating the results – tools like allowing you to graph a list of different variables along the slip surface or to display the detail forces on each slice, for example. These types of tools are vitally important to judging and being confident in the results.

Earlier it was noted that despite the extensive use of limit equilibrium methods in routine practice, the fundamentals of the formulations and the implications of the inherent assumptions are not well understood. An entire chapter is consequently devoted to a review of the fundamentals of limit equilibrium as a method of analysis. The chapter looks at the consequences of a pure statics formulation, what are the differences between the various methods, why are interslice forces important, what effect does the shape of the slip surface have, and so forth. In addition, the chapter discusses the limitations of the limit equilibrium method and discusses ways of overcoming the limitations. Gaining a thorough understanding of these fundamentals is essential to effective use of SLOPE/W.

SLOPE/W is one component in a complete suite of geotechnical products called GeoStudio. One of the powerful features of this integrated approach is that it opens the door to types of analyses of a much wider and more complex spectrum of problems, including the use of finite element computed pore-water pressures and stresses in a stability analysis. Not only does an integrated approach widen the analysis possibilities, it can help overcome some limitations of the purely limit equilibrium formulations. Although, it is not necessary to use this advanced feature as SLOPE/W can be used as an individual product, there is certainly an increase in the capability of the program by using it as one component of a complete suite of geotechnical software programs.

The very large number of options in SLOPE/W can be somewhat confusing, especially when you are using the software for the first time. Some semblance of order can be made of these options by thinking of a problem in terms of five components. They are:

- Geometry – description of the stratigraphy and shapes of potential slip surfaces.
- Soil strength - parameters used to describe the soil (material) strength
- Pore-water pressure – means of defining the pore-water pressure conditions
- Reinforcement or soil-structure interaction – fabric, nails, anchors, piles, walls and so forth.
- Imposed loading – surcharges or dynamic earthquake loads

Separate chapters are devoted to each of these main components.

More and more engineers are interested in conducting probabilistic types of stability. An entire chapter is devoted to the special subject of probabilistic analysis and sensitivity studies.

Examples are included throughout the book to illustrate features and explain behavior. In addition there is a special section devoted to illustrative examples, which are intended to provide ideas on how to model various situations. The examples are not intended to be complete case histories, but instead are intended to be simple illustrations used to highlight possible situations including complete submergence, stability on a synthetic liner, and bearing pressure.

At the end of the book is a chapter on theory. This chapter is included primarily as a reference, as a connection to the past and as information for those who are curious about the fundamental details used in SLOPE/W. Generally, it should not be necessary to spend too much time in this chapter to use SLOPE/W effectively.

This book is aimed at highlighting engineering concepts and stability analysis modeling techniques. This book is not aimed at describing all the software interaction commands and the meaning of all the various parameters in the dialogs boxes. These details are provided in the online help.

SLOPE/W has been designed and developed to be a general software tool for the stability analysis of earth structures. SLOPE/W is not designed for certain specific cases. SLOPE/W was not created specifically to design retaining walls, although SLOPE/W can certainly be used to assess the sliding stability of a gravity retaining wall, or to find the active earth forces on the wall. Likewise, SLOPE/W was not specifically designed for earth-reinforced retaining walls, but SLOPE/W can be used to analyze the stability of a wedge of soil that has been reinforced with a structural component such as a pre-stressed anchor, a soil nail, geo-fabric or some other material. Using a general tool such as SLOPE/W sometimes requires careful thought as to how to model a certain situation, but at the same time it greatly expands the range of possible situations you can model, which has been our main intention. The general nature allows for much greater creativity. Once you understand how the general features function, the types of problems that can be analyzed are primarily limited by your creativity. The main purpose of this book is to help you be creative, not to outline an endless list of rules you must follow.