# GUIDE FOR SELECTING AN APPROPRIATE METHOD TO ANALYZE THE STABILITY OF SLOPES ON RECLAIMED SURFACE MINES [1]

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and

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Abstract: Geotechnical engineers have long Recognized the seriousness of slope failures, and Numerous methods of slope stability analysis have been developed and are available. In addition, the number of computer programs which utilize one or more of the methods of analysis has been expanding rapidly. Unfortunately, there still exists considerable uncertainty about the accuracy of the various methods of analysis. Many of the programs allow rapid application of sometimes old and approximate methods. Often, program users do not have a sufficient background in the principles involved in the stability analysis. Selection of the appropriate method of analysis and input variables is paramount to obtaining the true margin of safety against slope failure. Use of an inappropriate method or nonrepresentative variables can lead to prediction of what appears to be a safe slope; however, post-reclamation failure indicates otherwise. In order to assist both the expert and novice analyzer of slope stability, a detailed investigation of the accuracy and applicability of six varied methods of analysis was undertaken. The assumptions and mechanics underlying each method were studied. The methods were used to evaluate the stability of several hypothetical slopes. Safety factors produced by the various methods were compared and method applicability was assessed. The six methods were also used to analyze the stability of three actual slope failures. Results of the investigation have been compiled into a table listing the methods and their respective applicability to various slope conditions. This table may be used as a quick reference to distinguish between the numerous methods of analysis. It provides those charged with ascertaining the stability of slopes a process to select the most appropriate method of analysis and to know the relative accuracy of the method. Use of the table developed through this study should promote, increased accuracy in the analysis of proposed returned-to-approximate-original contour slopes. Thus, post-reclamation failures can be reduced Through accurately analyzing proposed reclaimed slopes and altering potentially unstable designs.

Additional Key words: Slope stability, analysis, factor of safety, ground movements, slips, limit equilibrium methods, computer methods.

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## Introduction

Since 1977, surface mine operators have been required to restore their mined sites to the approximate pre-mining contours. Operators must place the spoil material against the face of the rock (highwall) that becomes exposed during mining. This reclamation practice has created some difficulties for mines located in steeply contoured regions such as Appalachia. Zipper and his co-workers (1985) investigated this practice and found numerous failures of reclaimed slopes. Factors contributing to failure of these slopes included: excessively steep regraded slopes, high pore water pressures in the fills, toes of slopes being located beyond the edge of the mining bench, and the increased speed of weathering of the newly exposed material. Failure of these slopes, although constructed as per federal regulations, indicate that it may not be possible to restore every site to the original contours.

Although not specifically cited as a cause of failure, inadequate analysis of the stability of reclamation slopes may be contributing to the list of failed reclaimed slopes. Regardless, if insufficient analysis is not the cause, improvements in the existing analyses may lead to lowering the number of failures. The stability of slopes against sliding is A serious problem and as such, Geotechnical engineers have led an effort To develop methods for the accurate analysis of the stability of slopes. As a result of these efforts, numerous methods of analysis have become available to the practicing engineer. Unfortunately, considerable uncertainty remains with regard to knowledge about the accuracy of each method. In addition, a large variety of different computer programs exists for the analyses of slope stability. Many of these permit the rapid application of sometimes old and approximate methods.

Occasionally, users of the computer programs have insufficient backgrounds in the geotechnical principals involved in slope stability analysis. They may not have a good knowledge of the type of information they will obtain from the computer solution to the problem. This can lead to selection of an inappropriate computer method for a specific slop analysis or the acceptance of inaccurate solutions. Either of these actions can result in the failure of the analyzed slope

In order to increase the ability of slope stability analysts to select the appropriate method of analysis for a given condition, a set of guidelines and recommendations has beer, developed. The recommendations allow the user to select the appropriate method of analysis and also provide him with a range in the relative degree of conservancy in the analysis.

## Selection of the Methods of Slope-Stability Analysis

Many methods of slope stability analysis have been developed in attempts to permit the quantitative assessment of the safety or stability of slopes. However, they can be classified into two approaches: deformation approach and limit equilibrium approach. The deformation approach is based on stress-strain characteristics of the soil and requires an appropriate analytical technique to determine the deformation of the slopes. Practical application of these methods have been limited. As such, engineers still rely on the limit equilibrium approach.

All limit equilibrium methods have similar features with regard to their computational procedures. A slip mechanism is postulated along a known or assumed failure surface. Then, a condition of incipient failure along the potential failure surface is assumed, i.e., a limit equilibrium state is reached. The shear resistance required for equilibrium is computed and compared with the available shear strength. The resulting ratio (available shear strength to required shear strength) is termed the factor of safety against slope failure. The factors of safety for a number of Trial slip surfaces are computed to find the minimum factor of safety, i.e., the most critical slip surface. The differences among the various methods of limit equilibrium result from the assumptions made in order to satisfy the equations of static equilibrium. These differences in assumptions lead to three different categories of limit equilibrium methods:

1. methods which satisfy overall moment equilibrium but not individual slice moment equilibrium,
2. methods which satisfy overall and individual force equilibrium, and
3. methods which satisfy overall moment and individual slice (complete) equilibrium.

The variety of solutions and computer programs available for each of these categories is extensive. Two of the most popular methods from each of the categories were chosen to evaluate the applicability and accuracy of each method. The method are listed in Table 1.

## Methodology

After selecting the methods of analysis shown in Table 1, three hypothetical slope cases were developed in order to test each method and compare the results. Parametric studies on these slopes were designed to yield as much information as possible about the applicability of the methods and to provide information for use in developing guidelines for selecting appropriate methods of analysis of slope stability. The slopes were divided in homogeneous and nonhomogeneous cases. The homogeneous slope is shown in Figure 1 . Shown in Figures 2 and 3 are the nonhomogeneous slopes used in the parametric study, a fill embankment on a clay foundation and a sloping core dam on a rock or firm foundation, respectively.

Three classes of stability problems as related to the drainage conditions were considered for each class of slope. The three classes included undrained, drained and partially drained problems. The ranges of the variables used in the sensitivity analyses of the homogeneous slope are shown in Table 2. The corresponding values used in the sensitivity analyses of the nonhomogeneous slopes are shown in Table 3.

In addition to the hypothetical slopes, the six methods of analysis were each used to analyze the stability of three actual slope failures. The data for these failures were obtained from the literature. They were chosen for their completeness with regard to soil property description, geometry, and behavior. Case 1 was a test embankment on sensitive clay (Ladd 1972). Case 2 was a flood control dam on a clay shale foundation (U.S. Army 1963). Case was a test embankment on soft sensitive cemented clay (La Rochelle et. al. 1974). These three cases provided circumstances which are reasonably representative of a majority of such failures.

## Results-of The Stability Analyses

The research program consisted of sensitivity and comparative analyses of the six methods of limit equilibrium slope stability analysis. Both drained and undrained conditions were considered for homogeneous and nonhomogeneous slopes.

In general, the most important parameter in the stability analysis was the shear strength, i.e., the soil's cohesion and friction angle. Regardless of the slope height or inclination from the horizontal, the strength parameters played the dominant role in determining the safety factor of the slope against failure. Lee (1989) provides extensive tables and figures illustrating the influence of the parameters listed in Tables 2 and 3. The results presented by Lee make it possible to determine the percentage of change in the safety factor for a given change in any of the variables used in the analysis.

The six analysis methods were used to predict the factor of safety of the slopes in each of the three case histories. The methods were also used to predict the failure surface. The results of the prediction are shown in Table 4. In each case, the actual factor of safety is known to be unity at the time of failure. Therefore, those predictions which come nearest to unity are the best methods at predicting failure, provided the assumed or predicted failure surface is representative of the actual surface. Examination of Table 4 shows that the Spencer method (SP) (Spencer 1967) provides the most nearly correct values of the factor of safety in each case. The failure surfaces predicted using the SP method, shown in Figures 4, 5, and 6, are representative of the actual surfaces.

In the comparative analyses, it was found that the Ordinary Method of Slices (OMS) (Peck 1967) can lead to unreasonably low (conservative) factors of safety. For total stress (undrained) analyses, the degree of conservatism ranged from 1 to 7 percent. For the effective stress analyses, the extent of the underestimate increased with increasing magnitude of pore water pressure. The Simplified Bishop (SB) method (Bishop 1955) (satisfies overall moment equilibrium) resulted in slightly lower factors of safety than the methods which satisfied all static equilibrium conditions. Factors of safety were in error by no more than +/- 7 percent. This was true in both the drained and undrained analyses. However, the SB method is limited to circular failure surfaces. The Simplified Janbu (Si) method (Janbu 1954) resulted in factors of safety within +/-10 to +/-15 percent of the correct value. The results were equally as accurate for the drained and undrained analyses and for both circular and non-circular failure surfaces. The Spencer method satisfied all conditions of equilibrium and gave accurate results for all practical conditions. The Lowe & Karafiath method (1960) and the Corps of Engineers (COE) method (1968) generally gave values of factor of safety which were too high (unconservative) for homogeneous slopes. The Corps of Engineers method generally gave values which were higher (less conservative) than the Lowe & Karafiath (LK) method.

## Selection-Guide to the Method of Slope Stability Analysis

Shown in Table 5 are the recommendations of the various methods of slope stability analysis for different slope problems and conditions. Four ratings (1 through 4) were established based on the degree of conservatism with 1 being the best method and 4 being the least suitable or not applicable method. To use Table 5, the type of slope problem must first be identified

(Cases A through F). Next, examine the left side of the table to determine the rating of analysis methods and select the method which yields the best rating, e.g., 1. If the performance level of a certain analysis method is desired, then look across the table for that particular method. The slope problem or condition which has a rating of 1 indicates that the given method of analysis is best suited for that particular type of slope problem.

For example, consider a slope problem of Case A. The OMS, SB, and SP method are recommended for use because they have the best rating. In addition, to check the slope problems for which the OMS method is most appropriate, examine across the table for the rating of the OMS method in each of the slope problems. OMS method is rated as I for cases A, B, D, and E. The comments on the right side of Table 5 also indicate that the OMS method can yield results of up to minus 50 percent in error (conservative) of the actual value of the factor of safety.

## Conclusions

A detailed investigation of the accuracy and applicability of six varied methods of slope stability analysis was undertaken. The assumptions and mechanics underlying each method were studied. The methods were used to evaluate the stability of several hypothetical slopes. Factors of safety produced by the various methods were compared and applicability of the methods was assessed. The six methods were also used to analyze the stability of three actual slope failures.

Results of the investigation have been compiled into a table listing the methods and their respective applicability to various slope conditions. This table may be used as a quick and convenient reference to distinguish between the numerous methods of analysis. It provides those charged with ascertaining the stability of slopes a process to select the most appropriate method of analysis and to know the relative accuracy of the method. Use of the table developed through this investigation should promote increased accuracy in the analysis of proposed returned-to-approximate-original contour slopes. Thus, post-reclamation failures can be reduced through accurately analyzing proposed reclaimed slopes and altering potentially unstable designs.

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Table 1. Slope Stability Methods Evaluated for Applicability Accuracy

| Equilibrium Conditions | Stability Analysis Method | Computer Program | Ref. |
|---|---|---|---|
| Moment and Force | Spencer (SP) | 1 | Spencer, 1967 |
| | Simplified Janbu (SJ) | 1 | Janbu, 1954 |
| Force | Lowe & Karafiath (LK) | 2 | Lowe and Karafiath, 1960 |
| | Army Corps of Engrgs (COE) | 2 | U.S. Army, 1968 |
| Overall Moment | Ordinary Method of Slices (OMS) | 3 | Peck, 1967 |
| | Simplified Bishop (SB) | 1,3 | Bishop, 1955 |

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2. K-SLOPE, Department of Civil Engineering, West Virginia University.
3. STABR, School of Civil Engineering, Univ. of California, Berkeley.

Table 2. Ranges of Variables for Sensitivity Analysis of Homogeneous Slopes.

| Parameter | Symbol | Range | Units |
|---|---|---|---|
| soil unit weight | $\gamma$ | 90 - 135 | $lb/ft^3$(pcf) |
| soil frictional angle | $\phi$ | 0 - 30 | degrees (°) |
| soil cohesion | C | 100 - 2100 | $lb/ft^2$(psf) |
| slope height | H | 10 - 100 | feet (ft) |
| slope inclination | B | 15 - 90 | degrees (°) |
| porewater pressure ratio | Ru | 0 - 0.5 | dimensionless |

Table 3. Range of Variables for Sensitivity Analysis of Nonhomogeneous Slopes.

**Undrained Analysis**

| Embankment / Dam Shell | | Foundation Soil / Dam Core | |
|---|---|---|---|
| C = 600 psf | $\phi = 0°$ | C = 400 psf | $\phi = 0°$ |
| C = 800 psf | $\phi = 0°$ | C = 2100 psf | $\phi = 0°$ |
| C = 1000 psf | $\phi = 0°$ | | |

**Drained Analysis**

| Embankment / Dam Shell | | Foundation Soil / Dam Core | |
|---|---|---|---|
| $\bar{C}$ = 0 psf | $\bar{\Phi} = 30°$ | $\bar{C}$ = 200 psf | $\bar{\Phi} = 11°$ |
| $\bar{C}$ = 200 psf | $\bar{\Phi} = 30°$ | $\bar{C}$ = 600 psf | $\bar{\Phi} = 18°$ |

Porewater Pressure Ratio: Ru = 0, 0.25, 0.50

Table 4. Results of Slope Stability Analysis for the Case Histories

| Case History (Ref.) | OMS | SB | SJ | SP | L & K | COE |
|---|---|---|---|---|---|---|
| (1) | 0.916 | 0.994 | 1.075 | 1.020 | 1.148 | 1.196 |
| (2) | 0.986 | 1.070 | 1.043 | 1.030 | 1.110 | 1.114 |
| (3) | 0.971 | 1.021 | 1.023 | 1.007 | 1.134 | 1.158 |

(1.) Ladd, C.C. 1972 Test Embankment on Sensitive Clay. Proceedings Specialty Conference on Performance of Earth and Earth Supported Structures, Purdue University, Lafayette IN, June 11-14, pp. 101-128.

(2.) U.S. Army Engineer District,Fort Worth, TX, 1963, Waco Dam: Report on Embankment slide and Reanalysis of Design. Vols. 1, 2, and 5.

(3.) La Rochelle et.al., 1974 Failure of a Test Embankment on a Sensitive Champlain Clay Deposit. Canadian Geotechnical Journal, Vol. 11., pp. 142-164.

Table 5. Selection Guide to Methods of Slope Stability Analysis

| Methods of Analysis | Types of Slope Problem/Situation A | B | C | D | E | F | Comments |
|---|---|---|---|---|---|---|---|
| OMS | 1 | 1 | 4 | 1 | 1 | 4 | Up to -50% error when deep failure surface exists in Case C and F. (Circular Surface) |
| SB | 1 | 1 | 1 | 1 | 1 | 1 | Up to -7% error for deep failure surface and high pore pressure. (Circular Surface) |
| SJ | 2 | 2 | 2 | 2 | 2 | 2 | Vary from 0 to +15% error in Case A. Up to -12% error for deep failure surface with high pore pressures in Case C. (Any Shape Surface) |
| SP | 1 | 1 | 1 | 1 | 1 | 1 | Best Method with longer time and greater effort. (Any Shape Surface) |
| L & k | 4 | 3 | 3 | 2 | 2 | 2 | Up to +50% unconservative in Case A. Vary from +7.5% to +17% in Case E & F. (Non-Circular Surface) |
| COE | 4 | 3 | 3 | 3 | 2 | 2 | Up to +60% unconservative in Case A. Vary from +8% to +18% in Cases E & F. (Non-Circular Surface) |

Rating System:
1. Best (within -5% to -10% conservative)
2. Okay (within +5% to +10% unconservative)
3. More Unconservative (within +15% to +20% unconservative)
4. No Good (over +20% unconservative)

Slope Problems

A) Homogeneous slope under undrained condition (Figure 1)
B) Homogeneous slope under drained condition, no pore pressure (Figure 1)
C) Homogeneous slope under drained condition with high pore pressures (Figure 1)
D) Nonhomogeneous slope under undrained condition (Figures 2 and 3)
E) Nonhomogeneous slope under drained condition with high pore pressures (Figures 2 and 3)
F) Nonhomogeneous slope under drained condition with high pore Pressures (Figures 2 and 3)

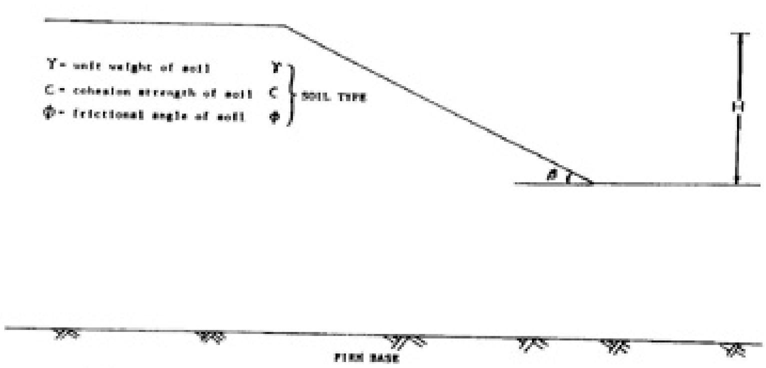


Figure 1. Typical Slope Geometry Used for the Homogeneous Soil Conditions.

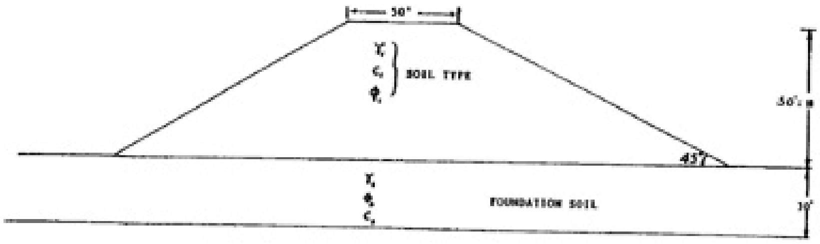


Figure 2. Typical Slope Geometry Used for the Nonhomogeneous Soil Conditions.

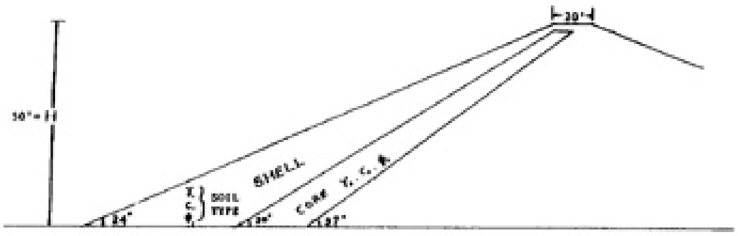


Figure 3. Typical Slope Geometry Used for the Nonhomogeneous Soil Conditions.

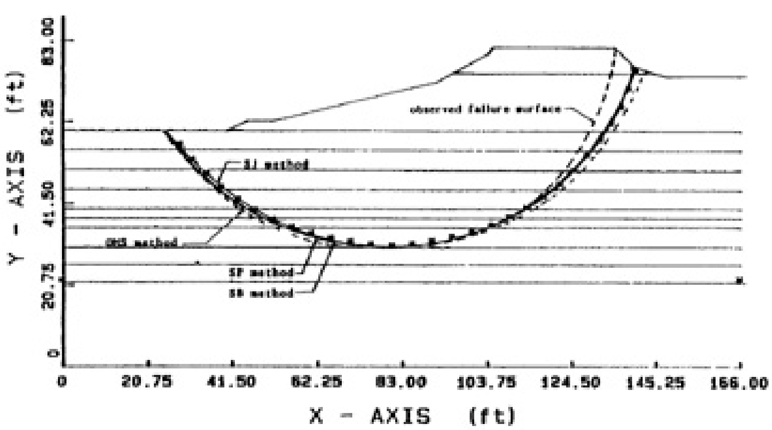


Figure 4. The Most Critical Slip Surfaces for the Test Embankment of Case History No.1.

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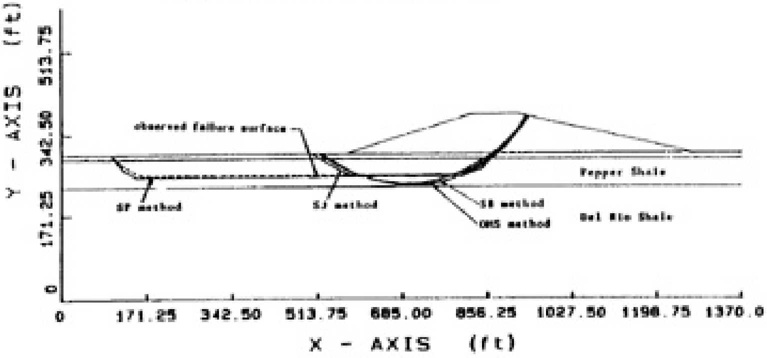


Figure 5. The Most Critical Failure Surfaces for the Case History No.2.

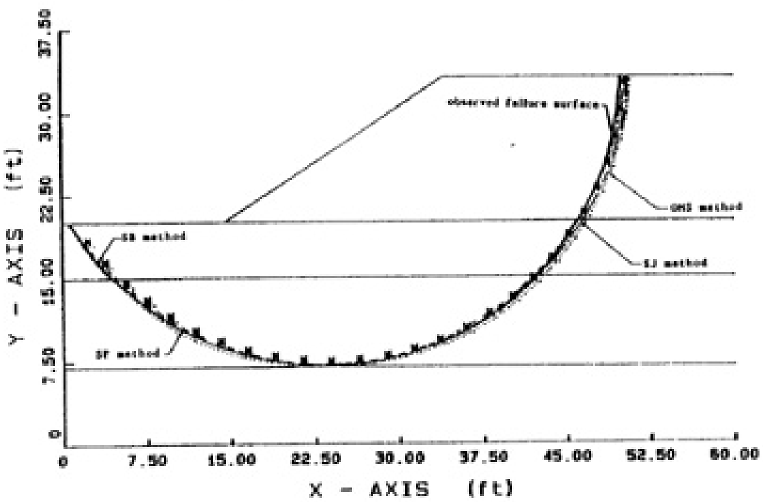


Figure 6. The Most Critical Slip Surfaces for the Test Embankment of Case History No. 3.