Software Used in Slope Stability Analysis

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Abstract—The slope stability is a very important problem in geotechnical engineering. Slope stability analysis using computers is an easy task for engineers when the slope configuration and the soil parameters are known. However, the selection of the slope stability analysis method is not an easy task and effort should be made to collect the field conditions and the failure observations in order to understand the failure mechanism, which determines the slope stability method that should be used in the analysis. Two dimensional slope stability methods are the most common used methods among engineers due to their simplicity. Today, both limit equilibrium method (LEM) and finite element method (FEM) based software are commonly used in geotechnical computations. In this paper, an attempt has been made to compile the available slope stability software information. A list of software available for the slope stability analysis is presented in this paper. Also a brief introduction and working principles of the software is discussed.

Key words: Software, LEM, FEM, Slope Stability, PLAXIS

I. INTRODUCTION

Methods for analyzing stability of slopes include simple equations, charts, spreadsheet software, and slope stability computer programs. In many cases more than one method can be used to evaluate the stability for a particular slope. For more sophisticated analyses and complex slope, soil, and loading conditions, computer programs are generally used to perform the computations. Computer programs are available that can handle a wide variety of slope geometries, soil stratigraphies, soil shear strength, pore water pressure conditions, external loads, and internal soil reinforcement. Most programs also have capabilities for automatically searching for the most critical slip surface with the lowest factor of safety and can handle slip surfaces of both circular and noncircular shapes. Most programs also have graphics capabilities for displaying the input data and the results of the slope stability computations.[12][14]

A. Methods of Analysing Slope Stability:

Once the various modes of failure are identified, a method of analysis should be adopted to assess the stability of the slope. There are two basic approaches to stability analysis: Limit equilibrium method (LEM) and Finite element method (FEM). [14] The principal difference between these two analyses approaches is that the LEM are based on the static of equilibrium whereas FEM utilize the stress-strain relationship or constitutive law. [4]

1) Limit Equilibrium Methods (LEM):

Analysis of slopes has traditionally been carried out by LEM, which are based on the principles of static equilibrium of forces and moments.[12] Several limit equilibrium methods have been developed for slope stability analyses. Fellenius (1936) introduced the first method, referred to as the Ordinary or the Swedish method, for a circular slip surface. Bishop (1955) advanced the first method introducing a new relationship for the base normal force. The equation for the FOS hence became non-linear. At the same time, Janbu (1954a) developed a simplified method for non-circular failure surfaces, dividing a potential sliding mass into several vertical slices. The generalized procedure of slices (GPS) was developed at the same time as a further development of the simplified method (Janbu 1973). Later, Morgenstern-Price (1965), Spencer (1967), Sarma (1973) and several others made further contributions with different assumptions for the interslice forces.

2) Finite Element Method (FEM):

The safety factor computed using the LEM is not uniquely determined, because it varies with the assumption made for the slip surface. The result may not be reliable if nonhomogeneous and anisotropic stratifications are considered. Therefore, better approach is to use finite element methods, which compute stress and strain distribution. These methods are particularly useful for the analysis of slope stability when it is subject to various types of loading or when it has complex geometry. In recent years, the finite element method has been widely used for quick initial stage slope stability analysis.[4][12][15]

The two approaches of stability analysis, one based on limit equilibrium (LE) formulations and the other based on finite element (FE) principles are widely used in practice. These LEM are well established for many years, and thus some of them are still commonly used in practice for stability analysis. Simplicity and relatively good results are the advantages of these methods. Since, the FEM are based on stress-strain relationship, stress redistributions are surely better computed even for a complicated problem. This has been found one of the advantages in FE simulations. [16]

II. SOFTWARE FOR SLOPE STABILITY ANALYSIS

A. Software Used For Stability Analysis:

Slope stability analyses today can be performed by using various computer based geotechnical software. Software utilizing limit equilibrium formulations has been used for many years. Similarly, finite element finite element software, based on constitutive laws and appropriate soil models, has drawn growing interest both of researchers and of professionals. Both LEM and FEM based software are commonly used in geotechnical computations. A list of software available for the slope stability analysis is presented in table 1. Also a brief introduction and working principles of the software is introduced in the following sections. [12]

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Software</th>
<th>Method of Analysis</th>
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<tbody>
<tr>
<td>1</td>
<td>SLIDE</td>
<td>Limit Equilibrium Approach</td>
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<tr>
<td>2</td>
<td>PLAXIS</td>
<td>Finite Element Approach</td>
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<td>3</td>
<td>SLOPE/W</td>
<td>Limit Equilibrium Approach</td>
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<tr>
<td>4</td>
<td>GSLOPE</td>
<td>Limit Equilibrium Approach</td>
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</table>
3) **SLOPE/W:**

SLOPE/W is the leading CAD software product for computing the factor of safety of earth and rock slopes. This program can effectively analyze both simple and complex problems for a variety of slip surface shapes, pore water pressure conditions, soil properties, analysis methods and loading conditions. It formulated in terms of moment and force equilibrium FOS equations. Limit equilibrium methods include Morgenstern-Price, GLE, Spencer, Bishop, Ordinary, Janbu etc. It allows integration with other applications. For example finite element computed stresses from SIGMA/W or QUAKE/W to calculate a stability factor by computing both total shear resistance and mobilized shear stress along the entire slip surface. Then a local stability factor for each slice is obtained. Using a Monte Carlo approach, program computes the probability of failure in addition to the conventional factor of safety. Program has also features like Specify many types of inter slice shear normal force functions, Use probabilistic soil properties, line loads, and piezometric lines, Transient stability analyses etc.

[20]

4) **GSLOPE:**

GSLOPE provides limit equilibrium slope stability analysis of existing natural slopes, unreinforced man-made slopes, or slopes with soil reinforcement. The program uses Bishop’s Modified method and Janbu’s Simplified method applied to circular, composite, and non-circular surfaces. Program handles complex geometries, with up to 20 material types, 9 piezometric surfaces, 100 external line loads, and 100 layers of reinforcement. Any consistent system of units can be used, including metric or British units. For pore pressures, Ru parameters and piezometric surfaces can be used alone or in combination. Slopes can be analyzed in either direction, and a seismic coefficient is provided for pseudo-static analysis.[9]

5) **STABLE WV:**

STABLE WV is a limit equilibrium methods based, windows software based on the STABL family of algorithms. It allows analysis using Bishop, Janbu and Spencer method. Besides tiebacks, nails and geogrids, stabilization using piles can also be analyzed. It also provides real-time visualization of slope geometry, soil profile, water table and inclusions as data is inputted.[21]

6) **FLAC/Slope:**

FLAC/Slope is a mini-version of FLAC (Fast Lagrangian Analysis of Continua) that is designed specifically to perform factor of safety calculations for slope stability analysis. It uses the explicit 2D finite difference method to model slope stability problems. It is a general analysis and design tool for geotechnical, civil, and mining engineers and can be applied to a broad range of engineering problems. It features: A graphical interface; automatic FOS calculation based on strength reduction technique; arbitrary slope geometries; multiple layers; pore pressure conditions; heterogeneous soil properties; surface loading; soil nails; rock bolts and structural reinforcement. The formulation can accommodate large displacements and strains and non-linear material behavior, even if yield or failure occurs over a large area or if total collapse occurs. [7][10]

7) **GALENA:**

GALENA is a limit equilibrium methods based, powerful and easy to use slope software system for Stability Analysis,

### Table 1: Software for the Slope Stability

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<tr>
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<th>Software</th>
<th>Approach</th>
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<tr>
<td>5</td>
<td>STABLE WV</td>
<td>Limit Equilibrium</td>
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<tr>
<td>6</td>
<td>FLAC/Slope</td>
<td>Finite Difference</td>
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<td>7</td>
<td>GALENA</td>
<td>Limit Equilibrium</td>
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<td>8</td>
<td>SVSlope</td>
<td>Limit Equilibrium</td>
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<td>9</td>
<td>CLARA-W</td>
<td>Limit Equilibrium</td>
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<td>CRISP 2D</td>
<td>Finite Element</td>
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<td>11</td>
<td>HYDRUS</td>
<td>Limit Equilibrium</td>
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<td>12</td>
<td>GEO FEM</td>
<td>Finite Element</td>
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<td>13</td>
<td>Phase$^2$</td>
<td>Finite Element</td>
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1) **SLIDE:**

SLIDE Software is a program for 2D slope stability analysis developed by RocscienceInc, Toronto Canada. It provides design and/or analyze natural slopes or manmade (engineered) slopes such as cuts, embankments and fills including earth dams and retaining structures such as tie-back walls, and soil nail structures, and waste dumps formed from mining or industrial by-products. It Provides 2D stability calculations in rocks or soils using these rigorous analysis methods: Spencer, Morgenstern-Price, General limit equilibrium; and non-rigorous methods: Bishop simplified, Corps of Engineers, Janbu’s simplified or corrected, Lowe-Karafiath and Ordinary/Fellenius. Searching of the critical slip surface is realized with the help of a grid or as a slope search in user-defined area. Modeling in SLIDE for the study was possible for external loading, groundwater and forces, like surcharge and from pseudo-static earthquakes. Program includes also probabilistic analysis using Monte Carlo or Latin Hypercube simulation techniques where any input parameter can be defined as a random variable. Probabilistic analysis determines the probability of failure and reliability index, which gives better representation of the level of safety. Back analysis serves for calculation of a reinforcement load with a given required factor of safety. Program enables finite element ground water seepage analysis.[16][19]

2) **PLAXIS:**

PLAXIS is a 2D finite element computer program for soil and rock analysis, developed by PLAXIS BV in cooperation with several universities including DUT in the Netherlands and NTNU in Norway. Real situations may be modeled either by a plane strain or an axisymmetric model. The program uses a convenient graphical user interface that enables users to quickly generate a geometry model and finite element mesh based on a representative vertical cross-section of the situation at hand. The program is applicable to many geotechnical problems, including stability analysis and steady-state groundwater flow calculations. This software contains several FE models and four main sub-routines. These routines are inputs, calculations, outputs and curve plots. The factor of safety versus displacement is plotted from the curve plots sub-routine. PLAXIS computes the FOS by successively reducing the soil strength parameters c and tan$\phi$ until the failure occurs. The strength parameters are automatically reduced until the final calculation step results in a fully developed failure mechanism. It used to perform deformation and stability analyses for various types of geotechnical applications. [1][15][18][23]
Back Analysis, and Probability Analysis, using the Bishop, Spencer-Wright and Sarma methods. It solves problems for mining excavations, embankments, cuttings, dams, and foundations. Also provides external forces to act at any point and angle on the slope, allowing simulation of bolts or inclusion of other forces. And calculation of approximated Phi values from SPT ‘N’ values or Plasticity Index. [8]

8) SV Slope:
SVSlope if formulated in terms of moment and force equilibrium factor of safety equations. Limit equilibrium methods include Morgenstern-Price, General limit equilibrium (GLE), Spencer, Bishop, Ordinary. This program allows integration with other applications in the geotechnical software suite. For example finite element computed stresses from SVSolid or pore water pressures from SVFlux can be used to calculate the factor of safety by computing total shear resistance and mobilized shear stress along the entire slip surface. The software also utilizes Monte Carlo, Latin Hypercube, and the Alternative Point Estimation Method (APEM) probabilistic approaches. [22]

9) CLARA-W:
CLARA-W is 3D slope stability program includes calculation with the help of these methods: Bishop simplified, Janbu simplified, Spencer and Morgenstern-Price. Problem configurations can involve rotational or non-rotational sliding surface, ellipsoids, wedges, compound surface, fully specified surfaces and searches. [2]

10) CRISP 2D:
CRISP (CRItical State soil mechanics Program) 2D is a finite element program incorporating critical state models of soil behavior. Program has been extensively used for many geotechnical problems, including retaining structures, embankments, tunnels and foundations. It has also been used in the analysis of footings, pile foundations, geotextile reinforcement, soil nailing, effect of anisotropy, slope stability, borehole stability and construction sequence studies. Program operates in two dimensional plane strain, or axisymmetric. [3]

11) HYDRUS:
HYDRUS is a limit equilibrium methods based, to use slope software system for Stability of embankments, dams, earth cuts and anchored sheeting structures. Each time step of water distribution can be analyzed separately. The slip surface is considered as circular and is evaluated using the Bishop, Fellenius, Morgenstern-Price or the Spencer method. It can be set as well as the different type of geotechnical reinforcement or earthquake effects. [11]

12) GEO FEM:
GEO FEM is a finite element package specifically intended for the 2D analysis of deformation and stability in geotechnical engineering projects and is built on the same original friendly platform as the GEO 4 - geotechnical software. Quadratic 3 node and 6 node triangular elements are available to model the deformations and stresses in the soil. It offers a variety of advanced soil models to simulate the nonlinear, time dependent soil behavior. In addition to the Mohr - Coulomb, Drucker Prager and Cam Clay models (elastoplastic type of hyperbolic model) are available. [13]

13) Phase2:
Phase2 Software has been used in geotechnical and mining engineering as a tool for the design and the analysis of tunnel, surface excavation and ore extraction and supports, developed by Rocscience Inc, Toronto Canada. However, few applications have been reported in the area of slope stability analysis. It is based on finite element method. [5][16][17]

B. Advantages of the Finite Element Method:
The advantages of a FEM to slope stability analysis over traditional LEM can be summarized as follows:

No assumption needs to be made in advance about the shape or location of the failure surface. Failure occurs naturally through the zones within the soil mass in which the soil shear strength is unable to sustain the applied shear stresses. Since there is no concept of slices in the FE approach, there is no need for assumptions about slice side forces. The FEM preserves global equilibrium until failure is reached. If realistic soil compressibility data are available, the FE solutions will give information about deformations at working stress levels. The FEM is able to monitor progressive failure up to and including overall shear failure. [4][15]

C. Research on Slope Stability Analysis:
Several research studies has been performed by the several authors to assess stability of slope. Brief summary of these studies is presented below.

Ismail et al. (2012) presented the factor of safety (FOS) and Strength reduction factor (SRF) computed by LEM and FEM with shear strength reduction technique for the four critical conditions are close to each other where the percentages of difference are all less than 6%. So, both methods are satisfactory for engineering usage in the analysis of earth-fill dam.

M. Rabie (2013) presented that classical LEM are highly conservative compared to the FEM. For assessment of the factor of safety for slope using the later technique, no assumption needs to be made in advance about the shape or location of the failure surface, slice side forces and their directions.

Maula and Zhang (2011) presented Most of the FOS obtained from Plaxis 2D program are slightly larger than those obtained from Geo Studio 2007 with only few exceptions. These results are reasonable and are expected. The differences between the two programs results are, however, small.

T. X. Tran presented the results obtained from the LEM and FEM analyses are very agreeable and reasonable. The LEM and FEM can be used to predict the dam stability as well as behaviors during design. Those methods can be considered useful approaches for solving the stability problems.

HAO Fengshan and WANG Lei presented the engineering case analysis shows that the application of model in evaluating slope stability can achieve good effect. The engineering example indicates that the new assessment method FEM is reasonable and feasible, and it provides a new idea for slope assessment. Finally, the safety factor of the reinforced slope is calculated, and the result shows that the calculated indexes can meet the requirement of the specifications.

J. Pruska presented the problems of stability of the natural slope that the associated safety factor corresponds to the one obtained by the c - φ reduction algorithm and comparison with classical methods. As compared to FEM
approaches, the plasticity based on Drucker Prager appears to yield comparable results. Generally numerical methods are more flexible when more general slip surfaces occur.

Sachpazis (2013) presented the slope stability at the three above mentioned discrete loading cases of the Carsington Earth Embankment Dam was analyzed and results between the Shear Strength Reduction (S.S.R.) Analysis Method and the Limit Equilibrium Analysis Method (LEM) based on the method of slices are comparable and similar.

III. CONCLUSIONS

Following conclusions are drawn from the review of research papers of slope stability analysis:

FEM has been shown to be a reliable and robust method for assessing the factor of safety of slopes. One of the main advantages of the FEM is that the factor of safety emerges naturally from the analysis without the user having to commit to any particular form of the mechanism a priori. The FE approach for determining the factor of safety of slopes has satisfied the criteria for effective computer aided analysis. The factor of safety differences between the finite element method and limit equilibrium method results are small. Any failure mode develops naturally, there is no need to specify a range of trial surface in advance. Multiple failure surfaces evolve naturally. LEM have been the primary method used in estimating the stability of slope for decades. However, due to some of the shortcomings of LEM, the FEM is a great tool to model non-linear stress-strain behavior of materials and understand the stability based on deformations. There is no concept of slices in the FE approach, there is no need for assumptions about slice side forces. No assumption needs to be made in advance about the shape or location of the failure surface.

REFERENCES

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