ISSN: 2278 – 7798
International Journal of Science, Engineering and Technology Research (IJSETR)
Volume 2, No 6, June 2013

A Review on Numerical Slope Stability Analysis

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Abstract:
Over several decades, the limit equilibrium method has dominated the usage over any other method for slope stability investigations. General two-dimensional limit equilibrium formulation was extended by development of a generalized model for three-dimensional analysis. Design of open pit slopes is becoming more and more important highways are being designed at perilous terrain. With the advancement in research numerous methods have been developed for slope stability analysis which discussed briefly in this paper. Uncertainty is a very crucial factor in slope design as an increase in one degree in cut slope might make a slope unstable and vice versa. Conventional slope practice is often based on factor of safety which can not explicitly address the uncertainty; this led to the development of probabilistic slope stability analysis. A case study from Deccan traps, in Mahabaleshwar, India has been studied using FLAC SLOPE 5.0, a finite difference code. Critical observations about the slope have been discussed in the paper

***Index Terms*—Slope Stability, Rock Mechanics, Numerical Analysis and Limit Equilibrium.**

I. INTRODUCTION

The stability of road cut highway slopes is always considered to be crucial as the slightest failure can be destructive in terms of monetary losses and harm to human lives. The cut slopes need to be carefully analyzed for this failure mechanism, prior to excavation, during excavation and post excavation. There are many different ways to compute the factor of safety of man-made and natural slopes including limit equilibrium, finite element methods, finite difference methods, discrete element methods, soft computing etc.

Appreciable research articles had been published since the publication of the first method of analysis by [1] that were either related to slope stability or involved slope stability analysis subjects. In recent years, the finite element method has been widely used for quick initial stage slope stability analysis, but limit equilibrium methods are still common in practice. Elasto-plastic analysis of the geotechnical problems has been widely accepted but for its routine use for slope stability is very limited. For certain types of complex geotechnical problems, finite element method offer real remuneration over linear equilibrium methods [2, 3, 4, 5]. Similar conclusions have been drawn by [6] in their analysis in Phase^2 and Slide using various examples. A detailed review of equilibrium methods of slope stability analysis is presented by [7].These methods include the ordinary method of slices, Bishop's modified method, force equilibrium methods, Janbu's generalized procedure of Slices, Morgenstern and Price's method and Spencer's method. The method of slices is based on dividing the slope mass into number of slices and analyzing stability of the failing mass taking into consideration the static equilibrium of the slices individually and the overall equilibrium of the failing mass as whole. The circular and noncircular limit equilibrium methods considers the equilibrium of the total failing mass only and therefore, the internal equilibrium of the sliding mass is not considered. Many methods have been presented to compute the factor of safety using limit equilibrium with a circular failure surface [8, 9, 10]. Simplified assumptions in 2D slope stability methods have led to factors of safety that differ from the more rigorous 3D slope stability analysis methods. In practice, 3D analysis of slope stability is not performed unless the geometry of the slope is very complex and complicated or the failure mechanism is compound. A study comparing a three-dimensional extension of the Bishop simplified method with other limit equilibrium solutions has been done [11] In addition to that three dimensional slope stability analysis has been done [12] using the method of columns. The model formulated [12] is an extension to the two dimensional general limit equilibrium formulation. Researchers have also analyzed the anisotropic characteristics of stratified rock mass described by ubiquitous-joint model; the calculation method of safety factor based on ubiquitous-joint model has been proposed; then the relationships between stratification dip angle, inclination and slope stability have been analyzed by FLAC3D[13]. 3D slope stability analysis method establishing a compatible velocity field and obtaining the factor of safety by the energy and work balance equation has been proposed by pervious researchers [14].

Several attempts have also been made by various researchers for probabilistic slope stability analysis by both finite element as well as linear equilibrium methods. The earliest papers appeared in the early 1970s [15, 16, 17, 18] and have continued steadily [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] More recently some workers have produced a detailed review of the literature on this topic, and also noted that the geotechnical engineering was slow to adopt probabilistic approaches to geotechnical designing, especially in traditional problems such as slopes and foundations [30, 31].

Manuscript received May 22, 2013.

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Zolfaghari [32] have presented simple genetic algorithm to search the critical non-circular failure surface in slope stability analysis and used it to solve the Morgenstern–Price method to find the factor of safety. The simple genetic algorithm used in this study has two purposes: firstly to find the critical non-circular failure surface in finite or infinite slopes, and secondly to solve the Morgenstern–Price method to calculate the factor of safety corresponding to the critical failure surface. The option of a supplement load and pseudo-static horizontal and vertical forces due to earthquake loading have been included to enable a comprehensive evaluation of slope stability. Several works in direction of optimization for minimization of factor of safety have also been done. Three-dimensional numerical analysis model has been established by fast Lagrangian explicit-finite-difference code of continua (FLAC3D); and some monitoring points were located in the slope thereby developing an internal routine (FISH) to calculate the interpolation displacements [33] Further, methodology included application of shear strength reduction method in Hoek-Brown criterion calculating the factor of safety. Runqiu and Qiang [34] have also used Explicit Lagraugian finite-difference method to simulate the behavior of structures built of soil, rock or other materials showing the explicit Lagrangian finite difference analysis more advantageous over routine methods for slope stability analysis. In finite element methods, the system of equations is solved in matrix form while in finite difference method explicit time marching schemes to solve the equations.

Xiaohuil et al. [35] computed the stress and the derivatives of the stress of the basic stochastic variables for the slope based on the technique of sliding surface stress analysis and on the theory of Elasto-plastic finite element, by using partial differential technique and incremental initial stress method. In the reliability analysis, the limit state function has been set up which can consider the direction of the sliding surface. Then, the reliability indices of the whole slope have been computed using the first order reliability method [36, 37]

Anderson and Howes [38] coupled general one-dimensional soil water infiltration scheme to an infinite slope stability analysis model to illustrate the potential of exploring the impact of soil suction and parameter variability in stability analysis. More generally, the desirability of two-dimensional modeling in the context of both soil suction/pore pressure models and stability analysis has been discussed in their work. Cai et al. [39] in their analysis have predicted the effects of horizontal drains on slope stability under rainfall by three-dimensional finite element analysis. Geographical information systems based on digital elevation models offer the potential to be able to map this variable and permit the modelling of a variety of stability criteria and surface processes including landslides, rock avalanches, pyroclastic flows and lava flows. Wadge [40] has discussed the potential of GIS modeling of gravity flows and slope instabilities.

Factor of safety has two commonly used definitions: The first is the strength reserving definition, which defines the factor of safety as the factor by which the shear strength of the soil would have to be divided to bring the slope into the state of critical equilibrium. The second is the overloading definition, which defines the factor of safety as the ratio of total resisting forces to total driving forces along a certain slip line.

II CASE STUDY OF MAHABALESHWAR

A road cut slope from Deccan traps of Mahabaleshwar has been critically analyzed using FLAC SLOPE 5.0. The other cut slopes from the region have also been previously analyzed using finite element and distinct element codes [41, 42, 43]. Prior to this analysis it is important to have geological know how of the slope. The strata in the area consisted mainly of basaltic rock mass (a layer of weathered basalt of thickness 6-9 m is under laid by basalt rocks). Typical field view is shown in Figure 1. The geometry of the slope has been correspondingly plotted using FLAC SLOPE (Figure 2). The geotechnical properties used for the analysis were determined in Rock testing facility (Department of Earth Sciences), IIT Bombay and are tabulated in Table 1.

Table 1: Geotechnical Properties of both rock type

Parameters	Massive Basalt	Weathered Basalt
Mass Density (kg/m^3)	2812	2000
Cohesion (Pa)	472000	300000
Tension (Pa)	35000	3500
Friction angle (°)	56.19	48

The Factor of safety has been calculated as 4.75 and the plot of shear strain in the rock mass is shown in Figure 3. Another critical observation was the development of tension crack whose length was determined to be 9.5 m. Figure 4 shows the velocity vectors of various grains of the rock mass of both weathered and un-weathered basalt.

There are numerous 2D and 3D codes available for stability analysis of slopes and other excavations. In general, no single analysis method is preferred over the other by agencies and therefore, the reliability of any remediation solution to any slope failure is completely left to the problem, its application and available input parameters. It is always better to cross check the results for confidence and better reliability.

It is essential that a research effort be devoted to gain better understanding of the slope failure analysis methods and to understand the weakness and strength of the methods and to point out practical aspects in the analysis procedures .

Figure 1: Typical field view of the area.

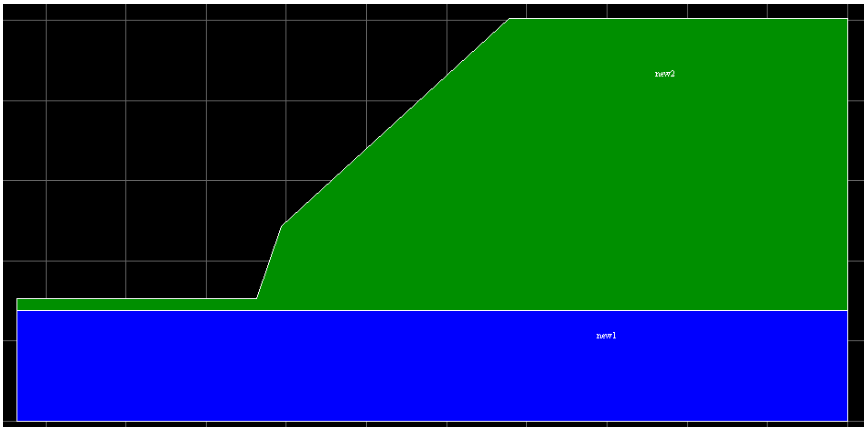

Figure 2: The geometry of the slope.

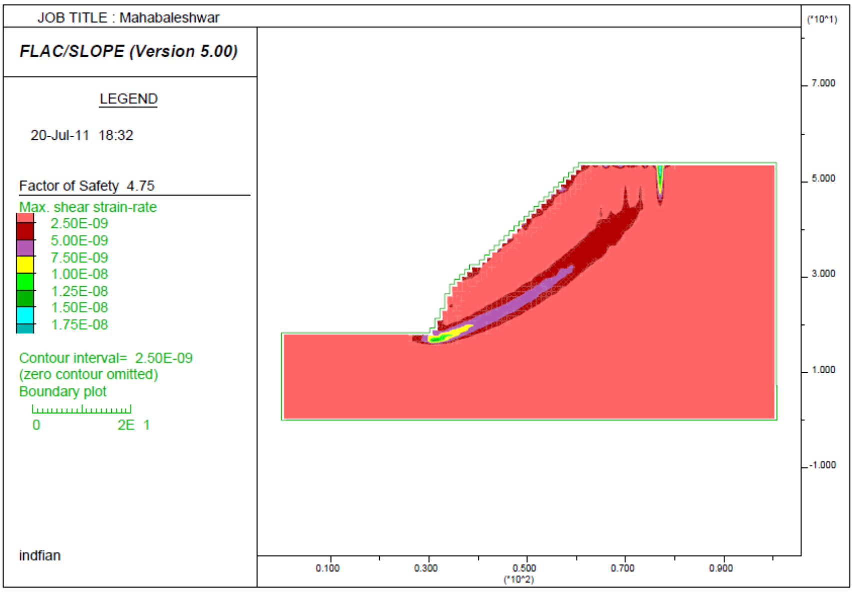

Figure 3: An analyzed slope showing shear strain and development of tension crack.

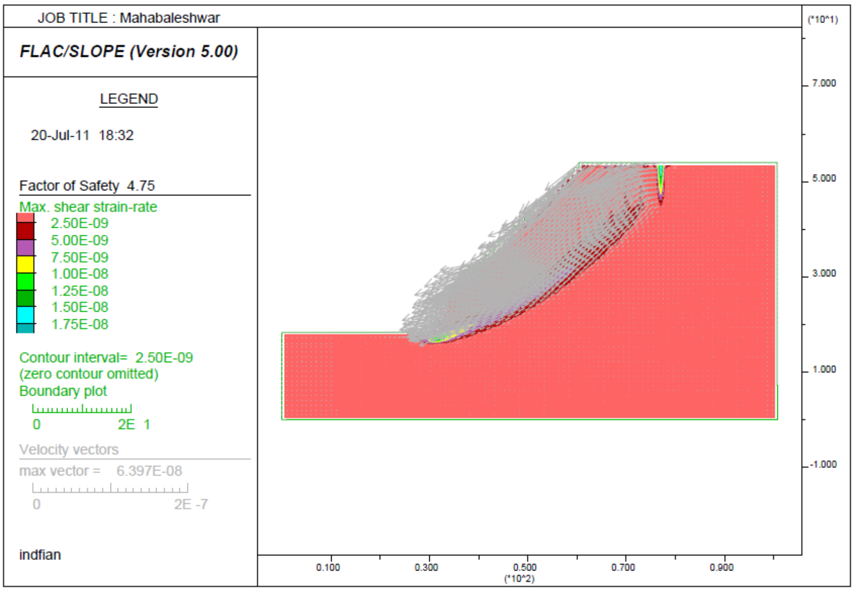

Figure 4: An analyzed slope showing velocity vectors of the grains of rock mass.

Conclusion:

Significant works by numerous authors have been done with regards to stability of slopes. Various methodologies used by them have been assimilated in the comprehensive review and discussed briefly with regards to the time span. A case study of a slope from Mahabaleshwar, India has been studied using finite element method. The study concluded that the slope is safe and has a factor of safety of 4.75. The plot of shear strain of the slope generated using FLAC SLOPE is in line with the observations and critical failure envelope has been studied. Another critical observation is the development of the tension crack of length 9.5m.

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