ZIBELINE INTERNATIONAL PUBLISHING

Geological Behavior (GBR)

DOI: http://doi.org/10.26480/gbr.02.2020.73.77

ISSN: 2521-0890 (Print)
ISSN: 2521-0491 (Online)
CODEN: GBEEB6

CrossMark

RESEARCH ARTICLE

A BRIEF REVIEW OF THE SLOPE STABILITY ANALYSIS METHODS

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ARTICLE DETAILS

Article History:

Received 14 April 2020
Accepted 15 May 2020
Available online 28 May 2020

ABSTRACT

One of the most common problem faced by geotechnical engineers is slope stability assessment. The predictions of slope stability in soil or rock masses is very important for the designing of reservoir dams, roads, tunnels, excavations, open pit mines, and other engineering structures. It is the importance of slope stability problem that has reasoned alternate methods for evaluating the safety of a slope. This study reviews the existing methods used for slope stability analysis. These methods are divided into five different groups which are; (a) Limit equilibrium method, (b) Numerical simulation method, (c) Artificial neural network method, (d) Limit analysis method, and (e) Vector sum method.

KEYWORDS

Slope Stability Analysis, Limit Equilibrium Method, Numerical Modeling, Artificial Neural Network, Vector Sum Method, Limit Analysis Method.

1. Introduction

The slope stability is always considered to be crucial as the slightest slope failure can be destructive in terms of monetary losses and harm to human lives. The slopes need to be carefully analyzed prior to econstruction of any structure , during construction and post construction. With the advancement to the 21st century, the world has seen marvels of geotechnical engineering, and human made structures including roads, railways embankment, dams constructed by hydraulical technique, earth dams, etc.. In this context, the study of the stability of natural slopes and human made slopes is a significant issue in geotechnical engineering.

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. In these methods, limit equilibrium method is a traditional method used to analise slope stability,' in which a single value of factor of safety is calculated to predict the stability of the slope. Afterward, some researchers developed finite element methods as a powerful technique in analyzing the slope stability problems. But the problem of slope stability is related to risk and reliability. Thus, a single factor of safety cannot be relied on for taking safety measures against slope failure. Analysing the reliability of slopes involves the calculation of reliability Index for a slope or alternatively probability of failure of a slope.

In both given approaches above, essential part is the search of the critical slip surface, i.e., critically deterministic slip surface or critical probabilistic slip surface, which is a constraint optimization problem. Various optimization techniques have their advantages in solving slope stability problems and ranging from simple optimization techniques, including non linear, linear programming, quadratic programming, dynamic programming and interior point method, etc., the advanced techniques such as simulated annealing, artificial intelligence algorithms was successfully used for analyzing slope stability. With the advancement of computers, it becomes easy to implement any of these methods.

As the detection of the slope failures is significant, it has been tried for decades to access the reasons behind the phenomenon. In this regard, most of the work done is based on the natural slope, rather man-made structures. However, when the same system is applied to anthropogenic structures, it fails to give the desired results. These limitations and failures are either caused by the usage of specified case studies or limited access to the database. Yet, another way that limits its application is related to information needed to utilize, including data obtained from rather complex tests or through costly monitoring systems. In a nutshell, there is no compact system to access the slope stability of both natural and anthropogenic slope at the same time. So, we need to use various methods to gain the required results. Therefore it is important 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 . For this purpose we reviewed the currently existing methods to select the best method according to the situation. We discussed these methods in details with their effectiveness in different working conditions in this review paper. By reading this review paper researcher would be able to select best method according to the situation.

As discussed, this paper reviews and discusses all contemporary methods for slope stability evaluation, divided into five different groups.

2. Discussion on Slope Stability Methods

2.1 Limit Equilibrium Methods

One of the most earliest technique developed to study the stability of slope is the Limit Equilibrium Method also called LEM. It require calculations of applied stress along with mobilized strength in the slope of over a trial slide surface. Here, safety factor is measured through these two given quantities. In this regard, trial failure surfaces calculate the minimum and

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Cite the Article: Sami Ullah, Muhib Ullah Khan and Gohar Rehman (2020). A Brief Review of the Slope Stability Analysis Methods. *Geological Behavior, 4(2): 73-77*

most critical value. There are several other methods available in this class. The assumptions related to the shape of the slide surface provides the significant difference between the various methods of Limit Equilibrium, such as Circular, plane, logarithmic, etc.. Whereas equilibrium equation is also based upon the same assumptions such as moment equilibrium or force equilibruim or in some cases both. Sometimes third dimension is considered, which is in perpendicular direction to plane of a crosssection, affecting the result of the slope (Albataineh, 2006). Mostly, Slice methods are used in limit equilibrium approach for slope stability analysis.

Limit Equilibrium method calculates safety factor by comparing of shear strength beside the sliding surface and the required force that can sustain the slope in equilibrium. For all failures that are of shear type, a rock can be supposed as Mohr-Coulomb material having shear strength stated as "c" cohesion and "φ" friction angle (Wyllie and Mah, 2004). As suggested, static equilibrium can be recieved in two ways. The first approach involves considering the equilibrium for whole mass of soil and then solve it for only free body. The second approach divides the soil into many slices, and then each slice must fulfill equilibrium condition of all forces (Wright, 2005).

Limit Equilibrium Slicing Method is popular among researchers of slope stability because of its well-established and tradional nature. The initial slice technique was established on engineering sensitivity, and then rigorous mechanics principle was discovered, hence the slice approaches got widespread acceptance in the 1950s and 1960s and then different limit equilibrium slice methods have been analyzed briefly and summarized (Fellenius, 1936; Bishop, 1955; Janbu, 1954; Price and Morgenstern, 1965; Spencer 1967; Fredlund et al., 1981; Duncan, 1996).

Mostly limit equilibrium approaches are established on slices method. Figure 1 shows a general formulation for these methods.

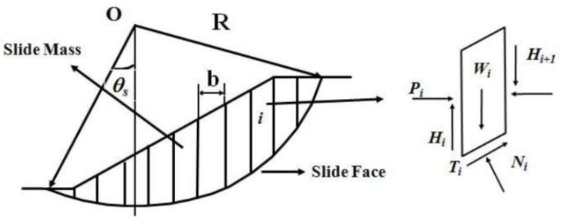

Figure 1: Slope slices and forces are acting on them

Some common features associated with these slices method summarize them as follow (Zhu et al., 2003).

- The sliding mass above the failure surface of failure can be divided into the finite numeral amount of slices. Vertical cutting of slices is more common but sometimes horizontal, and inclined cutting is also used by some researchers. Generally, the difference between different cuttings is not very common, besides vertical cutting is desired mostly by many engineers at present.
- For bringing the sliding body into equilibruim state, the strength of a slipping surface is moved to an equivalent degree. which means only a single safety factor is applied through the entire failure mass.
- Consideration of inter-slice forces is engaged to determine the problem accurately.
- Moment equilibrium equations or force can compute the safety factor.

Many other procedures applied to slices can satisfy static equilibrium completely. Different assumptions were made individually of these processes so as to get a solution. Whether we consider the equilibrium of an only free body or single vertical slices in a series, there will be further un-known (forces, positions of these forces, a factor related to safety, etc.) number of equilibrium equations. The problem for calculating a safety factor is ambiguous. So, to complete a balance between equations plus unknown's assumptions should be made.

3. Numerical Modelling Methods

When we use only the limit equilibrium analysis in designing a slope, the results can be inaccurate, if a slope has complex mechanism (progressively creeping, inner deformation, brittle fractures and liquefaction of the weak soil layers, etc.) (Stead and Marshall, 2001). Natural slopes have a possibility of heavy stress acting on failure mass that can mobilize the residual strength at some positions, whereas the shear strength is applying to other portion of failure mass. This kind of progressive failures can happen in those materials having fissure clays or highly consolidated materials having brittle nature. Numerical simulation technique can estimate such progressive failures.

Finite elements, finite differences and boundary elements numerical simulation techniques are currently applied to several geotechnical problems (Matsui and San, 1992; Griffiths and Lane, 1999). With respect to conventional methods of analyzing slope stability, numerical simulation method considers stress and strain relationship of slope such as constitutive relationship, and we can apply it to different type of meterial.

3.1 Numerical Modelling Techniques

There are two types of numerical modeling techniques. First is Slip Surface Stress Analysis (SSA), while second one is Strength Reduction Method (SRM), established during 1990s by Matsui and San; Swan; Griffiths and Lane (Zou et al., 1995; Swan et al., 1999).

Just like the LEM, the Slip Surface Stress Analysis Method by Wright in 1973; Yamagami in 1998 calculate slip surface initially, afterward analyze stress distribution of the surface after the convergence of numerical simulation, finally on the basis of the principle of weighted average calculates the safety factor (Wright et al., 1973; Yamagami, 1988). Many other scholars further analyzed this method for finding critical slip surface with sufficiently potential slip surfaces. Zou analyzed the first and potential range aspects of slide face over distribution of stress and further identified the most susceptible slide face and related factor of safety. Kim and Li found Gauss point to stress over finite element stress field, hence carriying out a regular examination of noncircular slide face (Kim and Lee, 1997). Giam and Donald suggested the pattern search method so as to select critical slide face and minimum factor of safety built upon stress field (Giam and Donald, 1988).

Second numerical simulation slope stability technique is based on strenghth reduction and it is more widely studied method as compare to SSA due to its simplicity and it can be easily led in current commercial numerical analyses software, e.g., ANSYS, FLAC UDEC, etc (Woodward, 1998; Faheem et al., 2004). The parameters of original shear strength are reduced in strength reduction technique until the slope failure occcur. The considering domain was discretized with equal body forces applied to its system. The yielded criteria adopted are basically Mohr-Coulomb criteria, but other yield criteria can also be used, e.g., Drucker-Prager criterion (Zheng et al., 2005). The numerical simulation techniques analyze stability of slope under different working conditions. e.g., Wu analyzed stability of slope under severe seismic events in central Asia by utilizing Finite Element program QUAKE/W and finite difference program FLAC3D (Wu et al., 2008).

Mainly, there are three types of slope failure criteria are used in numerical simulations methods:

- Convergence cannot be achieved in solving a non-linear equation after a pre-set maximum amount of iterations, and it is most commonly used criterion (Dawson et al., 1999; Lechman, 2000).
- There is a steep rise in displacement rate variation in system (Matsui and San, 1990).
- A mechanism for failure has been developed.

If we want to describe a critical failure surface using SSR method, the maximum shear strain and its increment should be defined and used. Cheng et al. have found the results of these two definitions similar most of the times (Cheng et al., 2006). Griffiths and Lane suggested the global use of the SRM by geotechnical researchers as a beneficial substitute for the traditional method of limit equilibrium.

Numerical modeling can help in assessing slope stability. FLAC is the software with widespread use in geotechnical engineering for numerical analysis. Fengshan and Lei studied specific steps for calculation and theoretic base of FLAC associated with suggestions on slope control (Fengshan and Lei, 2016).

The slope stability is dependent on safety factor, and over a long time, the limit equilibrium method is in widespread use before the development of 3D analysis. Kainthola et al. studied slope stability of Deccan traps, Mahabaleshwar, India using a finite difference code (Kainthola et al., 2013). Highways were planned at tough terrains using three-dimensional analysis besides critical observations declare that the factor of safety is the utmost crucial in slope stability analysis which is the beginning of probabilistic slope stability analysis method. Shear strength of soil or rock mass decreases in phases, till slope failure can determine the safety factor of slope in SSR method. Cala et al. suggested the utmost famous and important numerical method for slope stability assessment is the shear strength reduction method (SSR) (Cala et al., 2004). This technique is based on the mechanism of reducing shear parameters for soil after identifying the initial slip surface.

3.2 Numerical Modelling Types

Some of the numerical simulation types are given under:

3.2.1 Finite Difference Method

The Finite Difference Method (FDM) is very famous numerical simulation method. It is based on the argument that finite differences are adequate to represent in place of governing differential equations of elasticity theory. In geomechanics, this method is deemed to be the oldest among numerical methods. It was applied even before the beginning of the digital age. Here, in this method, differential equations set is reduced to linear equations system. These equations can be solved by using any classical techniques.

As shown in figure 2, the grid is superimposed to domain. As presented in figure 2, the sub-indices show position of point in the grid; e.g., *i,j* represents a point with coordinates (*xi, xj, k*) and so on. This method depends on calculation of the field equations, i.e., strain compatibility, equilibrium, etc. through finite difference formulas (Bobet, 2010).

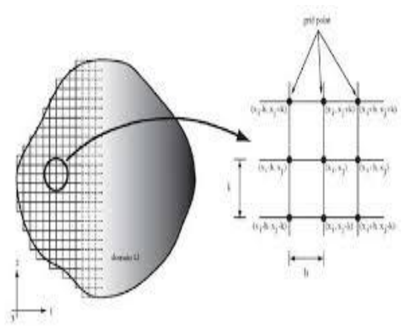

Figure 2: Finite Difference Grid in 2D

3.2.2 Finite Element Method

It is impossible to measure and estimate the progressive failure phenomena in the classical limit equilibrium. It is the reason for some scholars to propose the use of the finite element method to subdue some fundamental shortcomings and limitations in traditional methods for estimation. Several methods have been illustrated for analysis of slope stability through this method since last two decades. FEM widely uses gravity increase method and strength reduction method. However, In gravity increase method, the gravitational forces, such as weight, if increased gradually causes the unstability of slope. Here, safety factor can be defined as the ratio between gravitational acceleration in failure time and the actual gravitational acceleration (g). In the strength reduction technique, which has been discussed earlier, the parameters of slope strength are decreased to the point till the slope become unstable. Thus, the safety factor is measured asratio between actual strength parameters and critical strength parameters. The gravity increase method is very appropriate for the analysis of the stability of the embankment. The reason is the construction rate can be simulated in accordance with the increase in the rate of gravity loading on the embankment.

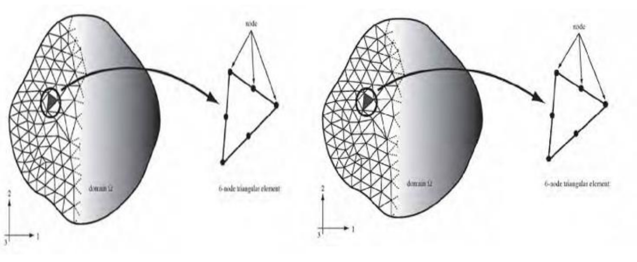

Figure 3: Finite Element Discretization in 2D

3.2.3 Boundary Element Method

In this method, discretizing the boundries of continuum is required. Figure 4 represents the contrast with other continuum methods. However, in Finite Element methods and Finite Difference methods , the entire medium is discretized.

In BEM, the solution is assumed at the boundaries, whereas the interior of the medium satisfies the conditions of equilibrium and compatibility. The main advantage is when we limit the the discretization to boundaries to point assessment while assuming all other measurements are considered constant. From 3D to 2D surface problem at the boundary convert from 2D to a line problem.

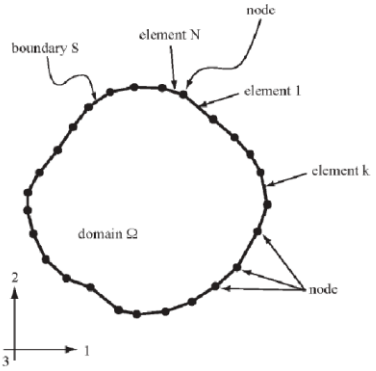

Figure 4: Example of Discretization with Boundary Elements in 2D

3.3 Artificial Neural Network

Artificial Neural Network (ANN) is a famous technique for Data Mining (DM) algorithms. It is applied in different types of field knowledge and various domains of subjects, e.g., web search, spam filters, recommender systems, and detection of frauds, etc (Domingos, 2012). Its applications are also well admissible in civil engineering sector. For example, ANNs are applied in mechanical and some other physical properties of jet grouting columns (Tinoco, 2018; Banimahd, 2002; Sakellariou and Ferentinou, 2005; Lu and Rosenbaum, 2003). The higher approach has enabled higher learning capabilities through the usage of algorithm and helped in modeling of complex nonlinear mappings.

3.4 Limit Analysis Method

Limit analysis method opted the idea of a supposed stress-strain relationship. It can be explained as; the soil is supposed to be a entirely rigid plastic material where flow rule is associated to it. Here, Limit analysis method provides a solution to many different problems while there is no need to carry out the step wise elastoplastic analysis.

As stated earlier, this method simulates the soil as an entirely plastic material. Where the associated flow rule is followed. According to this assumption of the soil behavior, it can run with two plastic bounding theorems and can prove as well (upper and lower bounds) [38]. As, we can bracket the actual collapse load from both above and below if both the upper and lower bounded solutions can be calculated by the bound theorems of limit analysis, which is particularly useful. This assumption is insignificant due to the built-in error check on the accuracy of the approximate collapse load (Yu et al., 1998). It is also valuable in such cases where exact solution cannot be determined e.g. slope stability analysis.

Limit analysis method depends on two theorems. The lower bound theorem defines lower bound estimate for accurate collapse load as any stress field statically admissible. The upper bound theorem defines that the external loads are upper bounds on actual collapse load when the power dissipated by any kinematically admissible velocity field is equalized with the power dissipated by the external loads.

3.5 Vector Sum Method

Ge was the first geoscientist who presented the vector sum method(VSM) by taking into consideration of both magnitude and direction of the force (Ge, 2010). VSM can be explained as "The ratio of the total force of resistance to the total driving force in the global sliding direction. The development of this method was based on actual stress of slope achieved from numerical analysis during some complex conditions" (Liu, 2017; Fuet al., 2017; Zou et al., 2017). Whereas, in the past, while utilizing this method, only force equation of sliding body in direction of sliding was considered. However, an assumption was made to determine the global sliding direction, which was based on the meshanism of sliding failure (Xiu-run, 2008; Guo et al., 2013; Wu, 2013).

In order to get an accurate potential slip surface, we can merge the complete stress state from the finite limit analysis into a limit equilibrium analysis. Here, the normal and shear stresses are measured according to any chosen slip surface. Now, two factors are considered simultaneously; the strength reserving definition of the factor of safety and vector characteristics of force. However, two aspects based on reserving of strength, force and moment equilibrium define the safety factor. If the vector composition law is used, because of the direction of resisting force, all the forces resisting along the potential surface of slip can be measured as a resisting force vector. Resultantly, division of soil shear strength by the factor of safety for bringing the slope to limit equilibrium state will help to obtain the total driving force vector and we can also establish a force equilibrium equation in the direction of global sliding surface. The moment equilibrium equation can also be obtained at moment center in identical manner. Thus, the global safety factor for the slope must be smaller than the two gained either from the force or from moment equilibrium equations.

4. 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.

In summary, most of the approaches so far proposed share the main limitations, which are related to its applicability domain or dependency on data which is difficult to obtain. In fact, the assessment of the stability condition of a given slope is a multi-variable problem characterized by high dimensionality.

This paper reviews and classifies the available methods for slope stability analysis. Limit equilibrium method is the oldest one, and the vector sum method is the youngest one. Every method has its own advantages and disadvantages depending on the conditions. The advantage of limit equilibrium method is its simplicity, and it takes a very short time. That is why it is the first choice of engineers. The disadvantage is its less accuracy than other methods and, we can't apply these methods in complex problems. While in comparison, other methods can solve complex problems. Also, we can also get the shear strain relationship in a slope. Within numerical simulation method, finite element method, using the theory of superposition, solves the physical problem through the division of the geometry into relatively small elements and measures the stress and strain in those elements and then assemble those again. However, the finite difference method has a different approach. It segregates the problem into little time steps with the use of finite difference formulations including forward, backward, and central differences and help predict the stresses and strains for next time step based on present time step. The gravity increase method(Finite Element Method) is very appropriate for the analysis of the stability of the embankment. The reason is the construction rate can be simulated in accordance with the increase in the rate of gravity loading on the embankment. Vector Sum Method is a relatively new method. For the multi-layer landslide, it is useful in performing the stability analysis.

References

Albataineh, N. 2006. Slope stability analysis using 2D and 3D methods. M.Sc. thesis, Akron University, Ohio, USA.

Wyllie, D. and C. Mah. 2004. Rock slope engineering 4th Edition. London, Spon Press.

Wright, S.G. 2005. Evaluation of soil shear strengths for slope and retaining wall stability analyses with emphasis on high plasticity clays.

Fellenius, W. 1936. Calculation of stability of earth dam. in Transactions. 2nd Congress Large Dams, Washington, DC.

Bishop, A.W. 1955. The use of the slip circle in the stability analysis of slopes. Geotechnique, 5(1), 7-17.

Janbu, N. 1954. Application of composite slip surface for stability analysis. in Proceedings of European Conference on Stability of Earth Slopes, Sweden.

Price, V. and N. Morgenstern. 1965. The analysis of the stability of general slip surfaces.

Spencer, E. 1967. A method of analysis of the stability of embankments assuming parallel inter-slice forces. Geotechnique, 17(1), 11-26.

Fredlund, D., J. Krahn, and D. Pufahl. 1981. The relationship between limit equilibrium slope stability methods. in Proceedings of the International Conference on Soil Mechanics and Foundation Engineering.

Duncan, J.M. 1996. State of the art: limit equilibrium and finite-element analysis of slopes. Journal of Geotechnical engineering, 122(7), 577-596.

Zhu, X., Z. Ghahramani, and J.D. Lafferty. 2003. Semi-supervised learning using gaussian fields and harmonic functions. in Proceedings of the 20th International conference on Machine learning (ICML-03).

Stead, D. and S. Marshall. 2001. The relationships between urban form and travel patterns. An international review and evaluation. European Journal of Transport and Infrastructure Research,1(2).

Matsui, T. and K.C. San. 1992. Finite element slope stability analysis by shear strength reduction technique. Soils and foundations, 32(1), 59-70.

Griffiths, D. and P. Lane. 1999. Slope stability analysis by finite elements. Geotechnique, 49(3), 387-403.

Zou, J.Z., D.J. Williams, and W.L. Xiong. 1995. Search for critical slip surfaces based on finite element method. Canadian Geotechnical Journal, 32(2), 233-246.

Swan, J., et al. 1999. Knowledge management and innovation: networks and networking. Journal of Knowledge management, 3(4), 262-275.

Wright, S.G., F. Kulhawy, and J.M. Duncan. 1973. Accuracy of equilibrium slope stability analysis. Journal of Soil Mechanics & Foundations Div, 99(Proc Paper 10097).

Yamagami, T. 1988. Search for critical slip lines in finite element stress fields by dynamic programming. in Proc. 6th Int. Conf. on Numerical Methods in Geomechanics, Innsbruck, Austria, Rotterdam: Balkema.

Kim, J. and S.R. Lee. 1997. An improved search strategy for the critical slip surface using finite element stress fields. Computers and Geotechnics, 21(4), 295-313.

Giam, S. and I. Donald. 1988. Determination of critical slip surfaces for slopes via stress-strain calculations. in Fifth Australia-New Zealand Conference on Geomechanics: Prediction Versus Performance; Preprints of Papers, Institution of Engineers, Australia.

Woodward, P. 1998. Stability of slopes with berms on rigid foundations. Geotechnical & Geological Engineering, 16(4), 309-320.

Faheem, H., F. Cai, and K. Ugai. 2004. Three-dimensional base stability of rectangular excavations in soft soils using FEM. Computers and Geotechnics, 31(2), 67-74.

Zheng, H., D. Liu, and C. Li. 2005. Slope stability analysis based on elasto-plastic finite element method. International Journal for Numerical Methods in Engineering, 64(14), 1871-1888.

Wu, A., et al. 2008. Validation for rock block stability and its application to rock slope stability evaluation using DDA method. Chinese Journal of Rock Mechanics and Engineering, 27(4), 664-672.

Dawson, E., W. Roth, and A. Drescher. 1999. Slope stability analysis by strength reduction. Geotechnique, 49(6), 835-840.

Lechman, J.B. 2000. The progression of failure in earth slopes by finite element analysis. Colorado School of Mines.

Matsui, T. and K. San. 1990. A hybrid slope stability analysis method with its application to reinforced slope cutting. Soils and Foundations, 30(2), 79-88.

Cheng, Y., W. Wei, and T. Lansivaara. 2006. Factors of safety by limit equilibrium and strength reduction methods.

Fengshan, H. and W. Lei. 2016. Application Study of FLAC in Analysis of Slope Stability. Physical and Numerical Simulation of Geotechnical Engineering, (23), 17.

Kainthola, A., et al. 2013. A review on numerical slope stability analysis. International Journal of Science, Engineering and Technology Research (IJSETR), 2(6), 1315-1320.

Cala, M., J. Flisiak, and A. Tajdus. 2004. Slope stability analysis with modified shear strength reduction technique. in Proceedings of the Ninth International Symposium on Landslides.

Bobet, A. 2010. Numerical methods in geomechanics. The Arabian Journal for Science and Engineering, 35(1B), 27-48.

Domingos, P.M. 2012. A few useful things to know about machine learning. Commun. acm, 55(10), 78-87.

Tinoco, J., A. Gomes Correia, and P. Cortez. 2018. Jet grouting column diameter prediction based on a data-driven approach. European Journal of Environmental and Civil Engineering, 22(3), 338-358.

Banimahd, M. 2002. Prediction of Undrained behavior of fine sands using Artificial Neural Networks. Master's dissertation, Tarbiat Modarres University, Tehran, Iran.

Sakellariou, M. and M. Ferentinou. 2005. A study of slope stability prediction using neural networks. Geotechnical & Geological Engineering, 23(4), 419.

Lu, P. and M. Rosenbaum. 2003. Artificial neural networks and grey systems for the prediction of slope stability. Natural Hazards, 30(3), 383-398.

Yu, H., et al. 1998. Limit analysis versus limit equilibrium for slope stability. Journal of Geotechnical and Geoenvironmental Engineering, 124(1), 1-11.

Ge, X.R. 2010. The vector sum method: A new approach to calculating the safety factor of stability against sliding for slope engineering and dam foundation problems, in Advances in environmental geotechnics, Springer, 99-110.

Liu, G., X. Zhuang, and Z. Cui. 2017. Three-dimensional slope stability analysis using independent cover based numerical manifold and vector method. Engineering Geology, 225, 83-95.

Fu, X., et al. 2017. Computation of the safety factor for slope stability using discontinuous deformation analysis and the vector sum method. Computers and Geotechnics, 92, 68-76.

Zou, Y., et al. 2017. Dynamic stability analysis of three dimensional slopes under seismic loads. Chin J Rock Mech Eng, 36(5), 1174-1184.

Xiu-run, G. 2008. Deformation control law of rock fatigue failure, real-time X-ray CT scan of geotechnical testing, and new method of stability analysis of slopes and dam foundations. Chinese Journal of Geotechnical Engineering, 30(1), 1-20.

Guo, M., et al. 2013. A new practical method for two-dimensional slope stability analysis. Disaster Advances, 6, 258-268.

Wu, Z. 2013. New analysis method for slope stability considering force-vector characteristics. Journal of Geotechnical and Geoenvironmental Engineering, 139(10), 1813-1816.