PNW-SLOPE – A new educational tool for geotechnical engineers

Thiago Fernandes Leao, Purdue University Northwest

Thiago Fernandes Leao is a Civil Engineer with Master of Science in Engineering at Purdue University Northwest. He has research interests in geotechnical and structural engineering. He has four years of industrial experience working as a Structural Engineer in Brazil and about one year working with parking structures in the US. He worked with projects ranging from small to large structures, reinforced and prestressed concrete, steel, masonry and foundations.

Prof. Jiliang Li P.E., Purdue University Northwest

Dr. Jiliang Li, D.Eng, Ph.D., P.E., M.ASCE, M.ARMA, is an Assistant Professor of Civil Engineering at Purdue University Northwest. Before coming back to teach at University, he had industrial experience in several States with projects consulting experience ranging from small residential, commercial and subdivision projects to larger scale State DOT and federal projects after additional courses and research study of geotechnical engineering at UAkron. Dr. Li has teaching and research interests ranging from engineering mechanics encompassing statics, dynamics, mechanics of materials and geotechnics (including geomechanics, rock mechanics, soil mechanics and engineering geology/hydrology), probability and statistics applications in civil engineering, and reliability based LRFD of geotechnical engineering, design of earth structures, soil and rock exploration, geotechnical and foundation engineering in particular. Dr. Li can be reached at Li1919@PURDUE.EDU and/or Li1919Purdue@Gmail.Com

Dr. Jinyuan Zhai, Minnesota State University, Mankato

Dr. Jinyuan Zhai joined the Mechanical Engineering faculty at MSU in August 2019. She earned her Ph.D. in mechanical engineering at The University of Akron in 2016. Before joining MSU, Dr. Zhai has been teaching Mechanical Engineering courses at Purdue University Northwest for one year. Dr. Zhai's research interests include solid mechanics, mechanics of materials and structures, machine design, mechanical testing, elasticity, plasticity and ductile fracture modeling of advanced engineering materials, finite element simulation.

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Abstract

In this study, a new educational tool, named PNW-SLOPE, to solve geotechnical engineering problems is presented. This tool consists of a program created in Microsoft Excel with the aid of VBA (Visual Basic for Applications) for calculations of 2D slope stability problems. Slope stability has been considered one of the most important topics in geotechnical engineering for years, so this is a subject that student should lay a good foundation background in the university studies. Another goal of PNW-SLOPE is to help improve the understanding of probabilistic concepts applied in geotechnical engineering, a topic often not properly studied at college. Reliability analysis has increasingly been incorporated in standards and design codes throughout the world, including geotechnical engineering structures, so it is important to understand the difference between deterministic and probabilistic approaches. Moreover, spreadsheets have widely been used in engineering and business world, but not so many civil engineering students use resources such as VBA which requires some computer programming skills. PNW-SLOPE demonstrates that it is possible to create advanced spreadsheets in Microsoft Excel when these additional resources are considered. The authors expect to help students in their learning, also encourage the application of computer programming skills in their spreadsheets for engineering problems.

Introduction

Evaluating the stability of slopes in soil is an important, interesting, and challenging topic in civil engineering. During the past 80 years, this subject has received extensive attention of researchers. Understanding of soil properties and analysis methods has improved considerably, resulting in many methodologies which try to include properly all the parameters involved in this kind of problem. The advances and experience are essential for this relevant topic of geotechnical engineering which have helped a lot in the development of human society.

Besides the advance in the soil mechanics knowledge, computational tools also have advanced in the past decades, leading to more capacity to solve complex problems. One important software that has been used for at least 20 years for general calculations and data analysis is Microsoft Excel. It is one of the most important computational programs in engineering, with a wide range of applications. Moreover, one of the resources offered by this software, the VBA (Visual Basic Applications) gives an extra tool for development of more complex spreadsheets, with buttons and windows to help the use of the spreadsheet. Due to the reasons above, Microsoft Excel was the platform considered for development of PNW-SLOPE.

Another important subject that has increasingly been considered in geotechnical engineering is the inclusion of uncertainty in the formulation of the problems. Probability-based approaches for slope stability analysis have been a topic of research for about 50 years, but now they are more widely spread. Designing standards and codes have tried to evolve and include reliability in every pertinent engineering situation. These facts gave students and professional an urge to improve their background in probability and statistics. It is important to know what the uncertainties are and what effect they will have on the results.

In geotechnical engineering, the application of uncertainty analysis is more challenging than in other fields, such as structural and mechanical engineering. The uncertainties in geotechnical engineering are largely inductive: starting from limited observations, judgment, knowledge of geology, and statistical reasoning are employed to infer the behavior of a poorly defined universe [1]. The pioneers like Casagrande [2] and Peck [3] started dealing with uncertainties in geological materials using the observational method. In this method, engineers make reasonable estimates of the parameters and the amounts by which they could deviate from the expected values. While uncertainty and reliability have a long history in geotechnical engineering, only in the last twenty years that several researches have made major advances in the use of more formal and rational approaches for reliability theory in geotechnical engineering [4].

The objectives of this research are to present a new educational tool for 2D slope stability analysis, show how reliability methods could be applied in geotechnical engineering problems and demonstrate how useful VBA programming language could be when used in the development of engineering tools. Even though many options of commercial and educational programs for slope stability calculations are available, the authors consider it

important that the creation of one more option, due to limitations of educational versions or lack of an easy user interface.

Spreadsheets in Engineering

The efficiency in the use of spreadsheets for engineering problems arises from the fact that the spreadsheet already contains routines for data input, data or graphical output and a range of algebraic and logic functions and that there is no requirement for a programmer to rewrite these routines from scratch again [5]. Some design routines are both laborious and time consuming because trial designs may have to be repeated several times before an acceptable solution is obtained. One way to deal with this is the use of additional features for optimization, such as the added in Solver in the case of Microsoft Excel.

Spreadsheets have been broadly used in engineering as teaching tools. Zaneldin and Ashur [6] presents an application of spreadsheets for teaching construction management concepts and applications. Zaneldin and El-Ariss [7] shows a broader application for civil engineering topics in general. Wong and Barford [8] presents an application of teaching through a user-friendly Excel VBA programming in chemical engineering. The use of Excel with VBA as a teaching tool represents a favorable environment for students to learn programming skills, since they are already familiar with Excel [9].

It is also possible to find a great number of references presenting useful applications and examples of spreadsheets for a variety of scientific disciplines. Davies [5] presents several examples of spreadsheets used for solving structural engineering design problems. Billo [10] shows how to implement numerical methods in engineering using Microsoft Excel. Bourg [11] presents a more practical application for real-world problems. This large number of materials with this purpose proves the importance of this subject nowadays.

Specifically, for geotechnical slopes some works have applied the use of spreadsheets for reliability analysis [12], [13], [14]. These works use matrix functions and Excel's Solver as optimization tool for calculations. Cao et al. [15] developed a tool for solving Monte Carlo simulations more efficiently at relatively small probability levels. Wang et al. [16] presented another application in geotechnical engineering to apply Bayesian equivalent samples to obtain meaningful statistics and probability distributions of geotechnical properties from the amount of observation data during the site investigation.

In addition to the extensive list of worksheet functions and array of calculation tools for scientific and engineering calculations, Microsoft Excel also offers a programming language that allows users to create procedures, sometimes referred to as Macros, which can perform further more advanced calculations or automate repetitive calculations. The name of this language is Visual Basic for Applications, or simply VBA.

VBA macros are usually referred to as procedures. They are written or recorded on a module sheet. A single module sheet can contain many procedures. There are two

different kinds of procedures: Sub and Function procedures. The difference between a function and a sub is that a function can return a value while this is not possible in a sub. Sub procedure is used to perform some actions. PNW-SLOPE could not be developed without the resources offered by VBA.

Slope Movements

The stability condition of slopes is a subject of study and research in soil mechanics, geotechnical engineering and engineering geology. Some of the situations considered for this kind of analysis are earth and rock-fill dams, embankments, excavated slopes, and natural slopes in soil and rock.

There are at least two different approaches to deal with slope stability analysis, both widely used and well-studied: limit equilibrium method and finite element method. Finite element method is based on solid mechanics by considering not only the equations of equilibrium but also those of compatibility, with an advantage of determining not only the factor of safety but also the displacements. In this study, only limit equilibrium method is considered, since this method is more simplified and adequate to be implemented in a spreadsheet environment. Due to the large number of limit equilibrium methods available, it is neither possible nor desirable to implement each of them, therefore three methods are being considered, each with different level of assumptions and simplifications.

The conventional approach consists of investigate the equilibrium of a mass of soil bounded below by an assumed potential slip surface and above by the surface of the slope [17]. The resulting shear stresses, induced along a potential or known failure surface, could exceed the shear strength of the soil and cause slope failure. The ratio of available shear strength to induced shear stress on a potential failure surface usually is referred as the factor of safety.

Stability analysis is used in the construction of transportation facilities such as highways, railroads, airports, and canals; the development of natural resources such as surface mining, refuse disposal, and earth dams; as well as many other human activities involving building construction and excavation [18]. Slopes failures involve such a variety of processes and causative factors that they afford unlimited possibilities of classification. For instance, they can be divided according to the form of failures, the type of materials moved, the age, the stage of development, or the cause of movements.

The failure surface can be divided in three main types: circular, non-circular and composite (Fig. 1). The failure shape will depend on the homogeneity of the materials in the slope. The non-circular failure surface may occur if there are weak layers or seams that start and end at or near the slope surface. This work is addressing only circular failure surfaces as shown in Fig. 1.
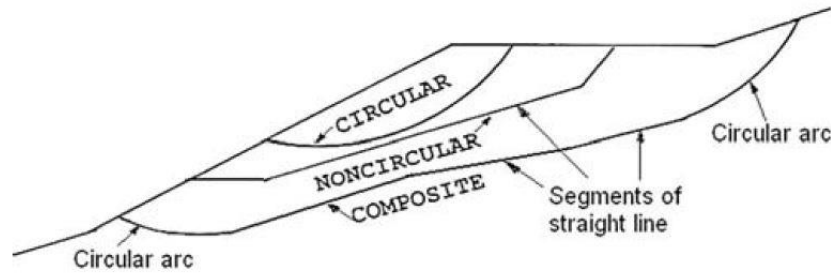
Figure 1: Types of failure surface

Reliability Analysis

Reliability-based analysis of slopes consists of considering the uncertainty of parameters, such as soil properties, in the calculations. The factor or margin of safety is represented in a form of probability density function (PDF). Probability of failure is calculated from this PDF. For evaluation if this probability is acceptable, target levels of reliability need to be established. This task involves evaluation of the potential consequences of failure and the required investment. This target probabilities of failure usually are based on historical estimates of reliability for common civil engineering structures.

Computational methods are used with the objective of compute probability of failure. They can be applied after the computational model, such as a method-of-slices slope stability program, and the statistical description of the material properties have been established. Monte Carlo simulation is being considered in this work. This method uses a random number generator to create large set of values of the uncertain parameters according to their prescribed probabilistic distributions and then computes the statistics of factor of safety from the results [1]. Its major advantages are that it is relatively simple to implement and can be used for almost any model or parameters. Its disadvantages are that it can require a great deal of computation which does not give much insight into the contributions of the individual parameters, and the subtleties of random number generation may lead to unexpected difficulties and errors.

PNW-SLOPE - Description

PNW-SLOPE is a program that runs within Microsoft Excel environment. The main purpose was to create an easy to use tool for those who want to learn slope stability analysis through direct applications. This part presents the main windows of PNW-SLOPE. Fig. 2 shows the initial screen after the program is open. It is possible to define the name of the project, authors and date. Each of the modules can be accessed through this screen. The button 'Define geometry' opens the window presented in Fig. 3, while button 'Deterministic Analysis' opens the window showed in Fig. 4. Fig. 5 shows the screen for definition of the probabilistic parameters. It is possible to choose which parameters will be considered in the analysis in terms of probabilistic distributions. The results can be visualized in the same screen.

After the project is defined and analyzed, the analysis results can be saved by clicking on the 'Save Project' button. This button opens an option for the user choose the destination

and name of the file. This file, which has the extension ".pnw" contains all the information created by the model. This file can be read by clicking on the 'Load Project' button. Another way to save the analysis is simply renaming the Excel file with the name of the project, since the spreadsheet always keep the last results.

One of the main features of PNW-SLOPE is that each part has instructions describing how to use the program. These files can be open by clicking on a small button included in the corner of each frame. For example, the instructions for step 3 in the geometry definition is presented in Fig. 6. This methodology allows the user to access each piece of information independently and quickly.

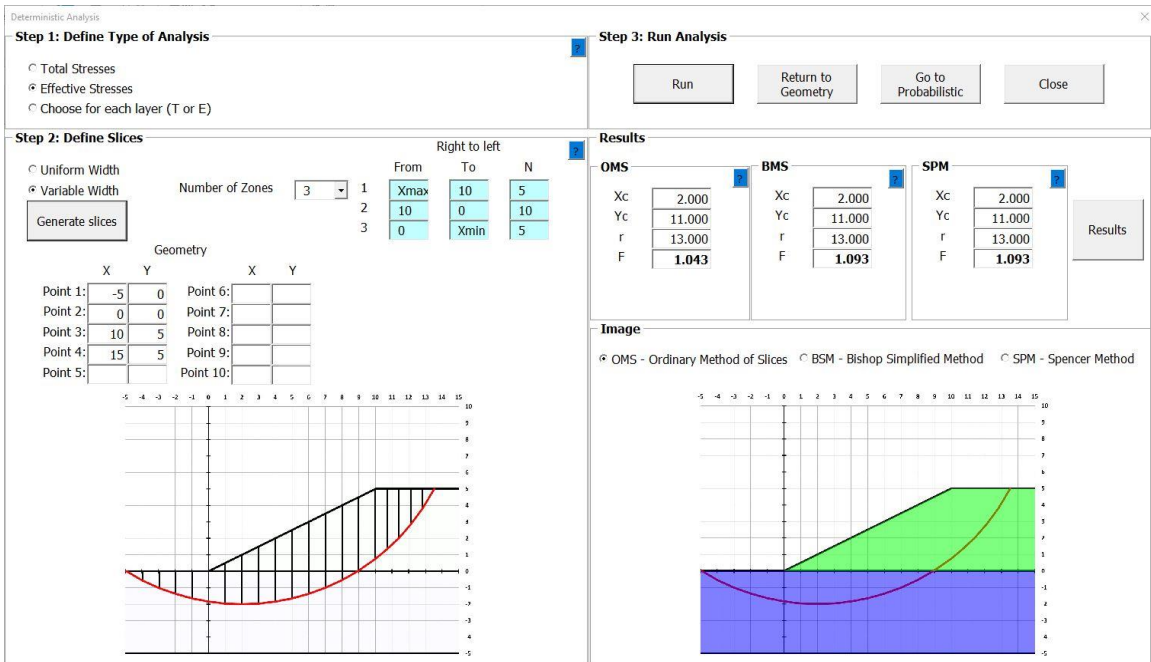Figure 2: Start screen

Figure 3: Geometry definition

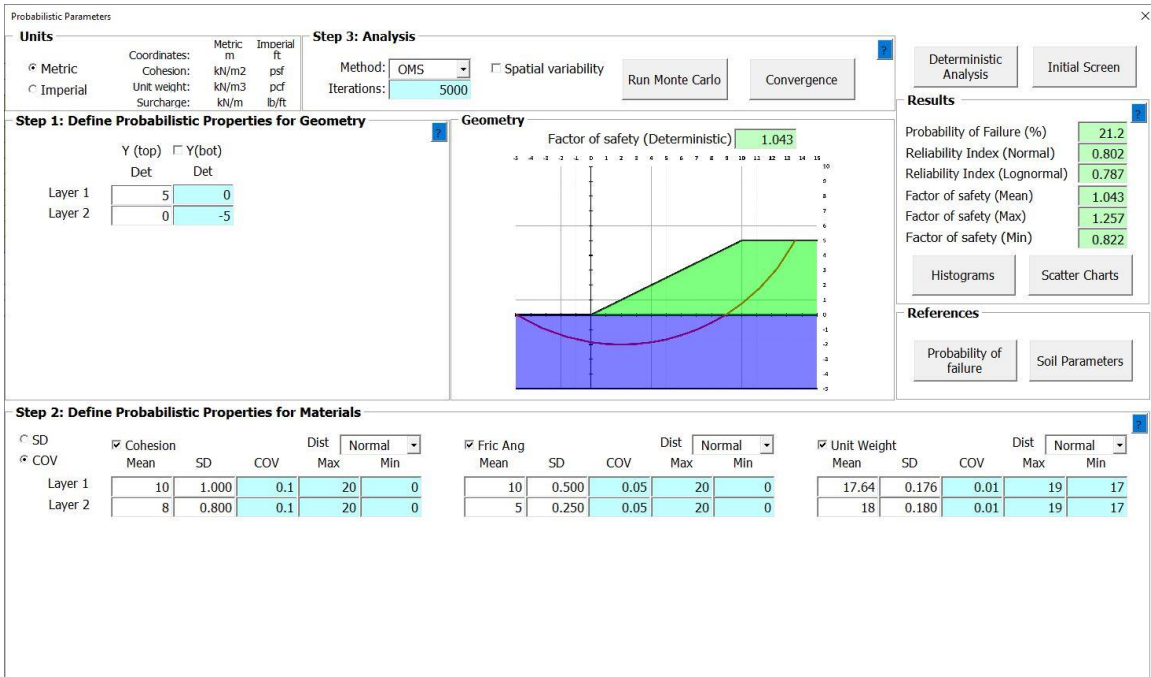**Figure 4: Deterministic Analysis**

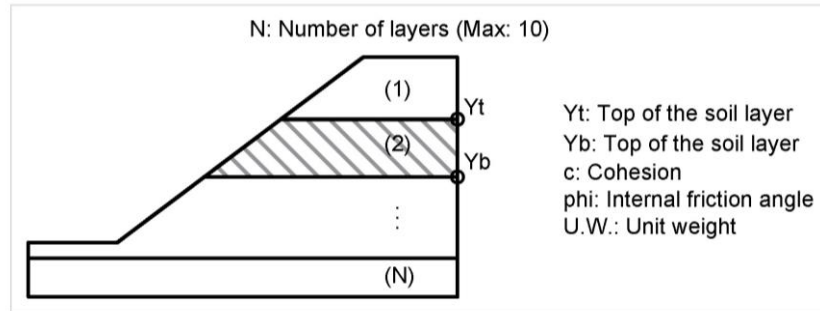
Figure 5: Probabilistic Analysis

Figure 6: Instructions for Step 3 at Geometry Definition Screen

PNW-SLOPE - Applications

PNW-SLOPE can be applied for different situations. Some of the applications are listed below:

- Short- and long-term analysis: when analyzing slopes, two situations could be considered: right after the end of construction and after a longer period. During the short-term analysis, depending on the soil material, drainage can or cannot occur. If the embankment is composed by sand and the foundation is composed by clay, each part should be addressed properly.
- Homogeneous and heterogeneous soils: the program allows up to ten layers with different properties to represent the soil profile. This information is obtained from soil testing, such as the Standard Penetration Test (SPT).
- Probabilistic analysis of soils with different variability: several situations can be represented considering different variability degrees for each layer independently. This allows an understanding of how each parameter impact on the probability of failure.
- Spatial variability: The program offers an option to define the spatial variability of each slice, which can be analyzed with isolate parameters or in groups. When more field investigation and soil testing are available, more statistical data become available and the probability of failure can be more accurately estimated.

Some results generated by PNW-SLOPE are presented in the following figures. Fig. 7 shows the results for deterministic analysis. The table in Fig.7 contains each input data considered and the results for each slice. This way of presenting the output is very useful for verification of hand calculations. Fig. 8 presents the distributions of the factor of safety and Fig. 9 the scatter data for load (Q) and resistance (R). Each point above the failure line represents a situation of failure. The probability of failure is the sum of all point in this region over the total number of simulations. Fig. 10 presents one example of how PNW-SLOPE can be used to compare slopes with different spatial variability being considered. Because the results are in spreadsheet, it is easy to export results from multiple analysis.

PNW-Slope - Results

													Units			
Project:	Example 1												Coordinates	ft	Surcharge	lb/ft
Author:	Thiago												Cohesion	psf	Forces	kip
Date:	8/28/2019												Unit Weight	pcf	Moments	kip-ft

Coordinates of the slope / Soil layers / Pore water pressure / Critical Slip Surface

Point	x	y	Layer	ytop	ybotton	γ	c'	Φ'	ru	a	Method:	Piezometric line		Critical Slip Surface		
1	-50.00	0.00	Soil 1	91.00	0.00	135.00	1780.00	5.00		T	Point	x	Y	Xc	Yc	r
2	0.00	0.00	Soil 2	0.00	-50.00	127.00	1600.00	2.00		T	P1			101.00	259.00	278.00
3	174.00	58.00									P2			Results		
4	256.50	91.00									P3			Method	Q	R	FS
5	400.00	91.00									P4			Ordinary Method of Slices	534073	700054	1.311
											P5						
											P6			Bishop Simplified Method	534073	710559	1.330
											Surcharge						
											q	xi	xf	Spencer Method	-	-	1.327

Table of Results for each slice

Slice	Coordinates at the midpoint of the slice			Width	Length of the Base	Angle at the Base	Angle at the Top	Cohesion and Friction Angle at Base		Weight	Pore water pressure	External Forces and Moments			Analysis	Sliding Forces		Resisting Forces for each method	
	Xm	Ytm	Ybm	b	ΔL	α	β	c'	Φ'	W	u	P	Q	Mp	T or E	Q - OMS	Q - BMS	R - OMS	R - BMS
1	306.00	91.00	72.83	33.00	49.08	47.76	0.00	1780.00	0.09	80930	0.00	0	0	0	T	59911	59911	92126	91288
2	273.00	91.00	41.61	33.00	42.08	38.35	0.00	1780.00	0.09	220010	0.00	0	0	0	T	136511	136511	89991	94523
3	248.25	87.70	23.40	16.50	19.46	32.01	21.80	1780.00	0.09	143226	0.00	0	0	0	T	75910	75910	45260	47461
4	231.75	81.10	13.84	16.50	18.70	28.07	21.80	1780.00	0.09	149811	0.00	0	0	0	T	70499	70499	44851	46509
5	215.25	74.50	5.72	16.50	18.10	24.28	21.80	1780.00	0.09	153200	0.00	0	0	0	T	62994	62994	44438	45572
6	198.75	67.90	-1.10	16.50	17.63	20.60	21.80	1600.00	0.03	153549	0.00	0	0	0	T	54018	54018	33222	33600
7	182.25	61.30	-6.72	16.50	17.25	17.00	21.80	1600.00	0.03	150631	0.00	0	0	0	T	44046	44046	32637	32844
8	161.57	53.86	-12.02	24.86	25.47	12.60	18.43	1600.00	0.03	218681	0.00	0	0	0	T	47697	47697	48205	48294
9	136.71	45.57	-16.41	24.86	25.07	7.39	18.43	1600.00	0.03	204733	0.00	0	0	0	T	26329	26329	47195	47153
10	111.86	37.29	-18.51	24.86	24.88	2.24	18.43	1600.00	0.03	183551	0.00	0	0	0	T	7176	7176	46207	46169
11	87.00	29.00	-18.37	24.86	24.89	-2.89	18.43	1600.00	0.03	155302	0.00	0	0	0	T	-7829	-7829	45238	45312
12	62.14	20.71	-15.98	24.86	25.10	-8.04	18.43	1600.00	0.03	119973	0.00	0	0	0	T	-16786	-16786	44315	44563
13	37.29	12.43	-11.30	24.86	25.54	-13.26	18.43	1600.00	0.03	77375	0.00	0	0	0	T	-17752	-17752	43491	43909
14	12.43	4.14	-4.19	24.86	26.23	-18.60	18.43	1600.00	0.03	27118	0.00	0	0	0	T	-8650	-8650	42861	43345
15	0.00	0.00	0.00	0.00	0.01	-21.30	0.00	1600.00	0.03	0	0.00	0	0	0	T	0	0	9	9
16	-0.01	0.00	0.00	0.00	0.01	-21.31	0.00	1600.00	0.03	0	0.00	0	0	0	T	0	0	9	9

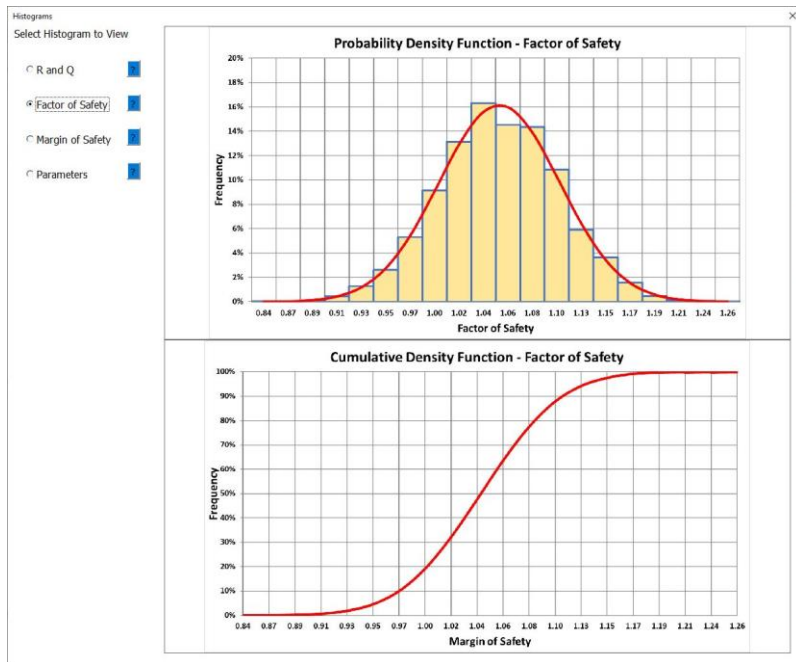**Figure 7: Results for Deterministic Analysis**

Figure 8: Results for Probabilistic Analysis - PDF and CDF
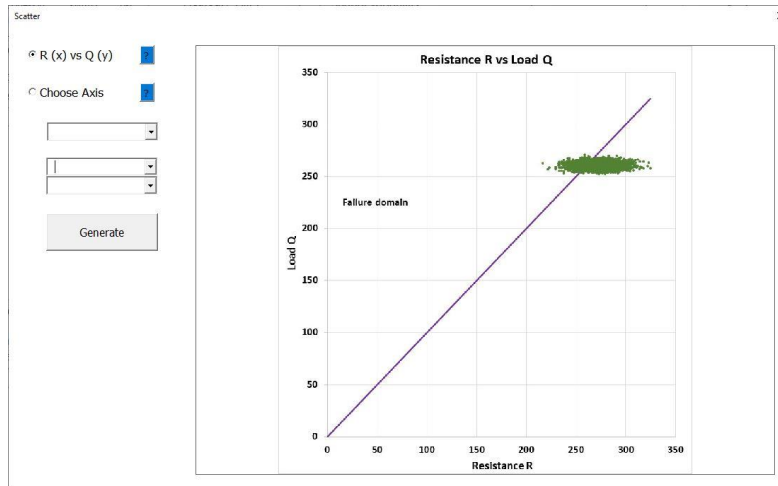
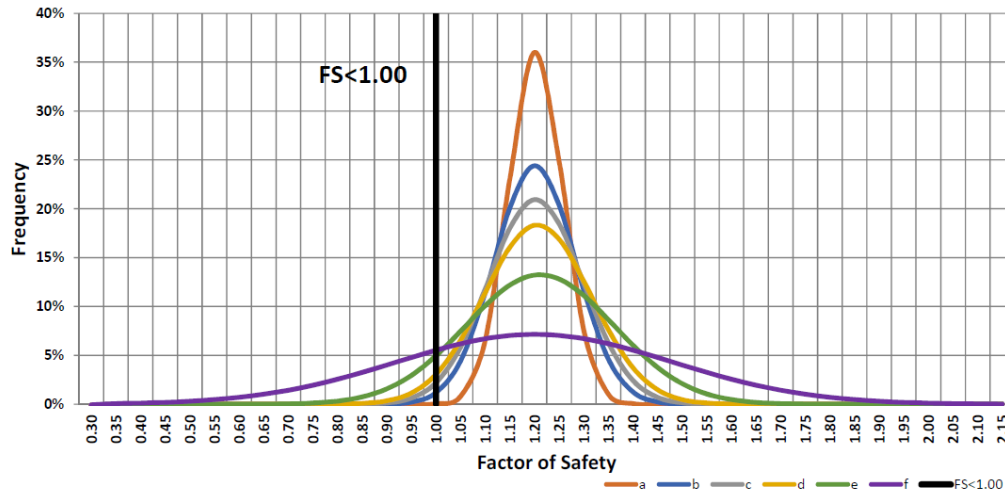**Figure 9: Results for Probabilistic Analysis - Scatter data**

Figure 10: Study of six different variability degrees

Concluding Remarks

The objective of this paper was to present PNW-SLOPE, a new tool to perform 2D slope stability analysis. This initial part focused on the first two modules of the program: geometry definition and deterministic slope stability analysis. Some of the options offered by PNW-SLOPE were the inclusion of up to ten layers with different properties, consideration of pore pressure water and external forces. Some relevant aspects of reliability analysis in geotechnical engineering were demonstrated with the third part of PNW-SLOPE. This is a relevant topic nowadays, since one of the main challenges for engineers is to use the maximum of data provided by investigations in a more realistic approach. In deterministic analysis, the slope is evaluated based on a single factor of safety while in probabilistic approach the factor of safety is represented by a range of values, usually represented as a probability density function. More information is required to properly account for the variability of parameters. It is important to note that reliability theory does not invalidate the factor of safety calculations. Instead, it extends the meaning of deterministic analysis by giving additional information to help the

10

engineer interpret the results. The advantages when considering a programming language in the development of spreadsheets were demonstrated with PNW-SLOPE. VBA has an immense potential to increase the capacity of spreadsheets developed in Excel by students and researches, and programming skills plays a fundamental role in this project tasks.

References

1. G. B. Baecher and J. T. Christian, "Reliability and statistics in geotechnical engineering", John Wiley & Sons, 2005.
2. A. Casagrande, "Role of the calculated risk in earthwork and foundation engineering", Journal of the Soil Mechanics and Foundations Division, vol. 91, no. 4, pp. 1-40, 1965.
3. R. B. Peck, "Advantages and limitations of the observational method in applied soil mechanics," Geotechnique, vol. 19, no. 2, pp. 171-187, 1969.
4. J. T. Christian, "Geotechnical engineering reliability: How well do we know what we are doing?", Journal of geotechnical and geoenvironmental engineering, vol. 130, no. 10, pp. 985-1003, 2004.
5. S. R. Davies, "Spreadsheets in structural design", Longman Publishing Group, 1996.
6. E. Zaneldin and S. Ashur, "Using spreadsheets as a tool in teaching construction management concepts and applications", American Society of Engineering Education (ASEE) Annual Conference, pp. 22-25, 2008.
7. E. Zaneldin and B. El-Ariss, "Using spreadsheets and vba for teaching civil engineering concepts," J. Education, Informatics and Cybernetics, vol. 2, no. 1, pp. 28-36, 2011.
8. K. W. Wong and J. P. Barford, "Teaching excel vba as a problem-solving tool for chemical engineering core courses", Education for Chemical Engineers, vol. 5, no. 4, pp. e72-e77, 2010.
9. T. L. Chambers, "Teaching engineering analysis using vba for excel", in Proceedings of the 2006 ASEE Gulf-Southeast Annual Conference, 2006.
10. E. J. Billo, "Excel for scientists and engineers: numerical methods", John Wiley & Sons, 2007.
11. D. M. Bourg, "Excel Scientific and Engineering Cookbook: Adding Excel to Your Analysis Arsenal", O'Reilly Media, Inc., 2006.
12. B. Low and W. H. Tang, Efficient reliability evaluation using spreadsheet", Journal of Engineering Mechanics, vol. 123, no. 7, pp. 749-752, 1997.
13. B. Low, R. Gilbert, and S. Wright, "Slope reliability analysis using generalized method of slices", Journal of Geotechnical and Geoenvironmental Engineering, vol. 124, no. 4, pp. 350-362, 1998.
14. B. Low and W. H. Tang, "Efficient spreadsheet algorithm for first-order reliability method", Journal of engineering mechanics, vol. 133, no. 12, pp. 1378-1387, 2007.
15. Z. Cao, Y. Wang, and D. Li, "Practical reliability analysis of slope stability by advanced monte carlo simulations in a spreadsheet", in Probabilistic Approaches for Geotechnical Site Characterization and Slope Stability Analysis. Springer, pp. 147-167, 2017.

16. Y. Wang, O. V. Akeju, and Z. Cao, "Bayesian equivalent sample toolkit (best): an excel vba program for probabilistic characterisation of geotechnical properties from limited observation data", Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 10, no. 4, pp. 251-268, 2016.
17. U. A. C. of Engineers, "Engineering and design: slope stability, engineering manual," 2003.
18. Y. H. Huang, "Slope stability analysis by the limit equilibrium method: Fundamentals and methods," American Society of Civil Engineers, 2014.