Risk Analysis of the Slope Stability of Embankment Dam Using Three Different Approaches

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Abstract

Safety management is an essential part of dam industry in order to ensure that the safety of the structure has been satisfied. Dam safety management involves risk related problems and subsequently taking decisions under uncertain situations. Vulnerability of people lives, properties and lifelines due to dam failure always has been an important challenging issue to dam owners. Conventional approaches do not take into account many threatening risks to dam safety, and their focus is to obtain a safety factor which concludes to rules and regulations leading to unclear indication of dam safety level. Nowadays, risk evaluation methods are widely used to determine the safety level of dams which provide this opportunity for engineers to consider many uncertain input data for dam safety decisions. Monte Carlo simulation method is one of the risk assessment tools for slope stability evaluation. In this method a repeated deterministic analysis of slope stability with respect to the probability distribution of input parameters leads to the appropriate solutions of the selected case. In the present paper, it is attempted to illustrate the application of Monte Carlo method as a powerful tool to analyze the slope stability of an embankment dam. In this regard, upstream slope of Doosti dam located in Iran has been considered as a case study. The analysis has been done using Mohr-Coulomb constitutive model by SLOPE/W software, version 6.02. Bishop, Janbu and Spencer methods are employed to compute the reliability index of upstream slope of dam. The results of risk analysis indicate that Bishop approach has the lowest reliability index among the selected methods with a reliability index of 5.991.

Key words: Embankment Dam, Monte Carlo Simulation, Risk Analysis, Safety Management, Slope Stability, Doosti dam.

1. Introduction

Slope stability is one of the most important issues of concern to geotechnical engineering. Analysis of slope stability is composed of many uncertainties pertinent to lack of accurate geotechnical parameters, inherent spatial variability of geo-properties, change of environmental conditions, unpredictable mechanisms of failure, simplifications and approximations used in geotechnical models. Due to the importance of dam projects and its pertinent costs, determination of dam performance has a significant consequence to decision makers. With respect to the uncertainties of geotechnical parameters, utilizing risk analysis is inevitable in dam projects.

Conventional approaches do not take into account many uncertainties in their calculations quantitatively. Also, several conservative safety factors are using to cover some uncertainties which in most cases are more than required, and in some cases less than what is necessary. Actually, it is not possible to distinguish the accurate effect of these safety factors on safety level. By contrast, in probabilistic approaches the safety determination applies more accurately and clearly (Manafi Ghorabaei and Noorzad, 2011).

Based on conventional methods of design, many events have been occurred leading to damages to structure. It is necessary to follow some methods resolving current requirements in addition to considering future probable incidents. Risk evaluation provides this opportunity to take into consideration many uncertain variables related to dam safety and applying quantitative and qualitative analyses. It will yield to proper economical and functional decisions in dam safety field. Risk management includes risk analysis, risk evaluation and risk control. Risk control is a part of risk management which includes examination of different options of encountered risks such as risk reduction, acceptance of risk and avoidance of risk (Fell and Hartford, 1997; Grocott et al., 1999).

Examination of dam slope stability after construction is an important issue of dam safety evaluation. It is possible to use the probability distribution of strength parameters of earth dam materials to evaluate dam slope stability with risk based approaches.

Monte Carlo simulation is a powerful tool to slope stability risk analysis. An iterative process using deterministic methods of slope stability analysis is applied in this technique. Monte Carlo simulation is a popular method of slope stability risk analysis among engineers because of its simplicity and no need of comprehensive mathematical and statistical knowledge. This Method consists of four steps as below (Hammond *et al.*, 1991; Chandler, 1996):

1. Choosing a random value for each input variable according to assigned probability density function.

2. Calculating factor of safety by using a proper deterministic slope stability analysis method (such as Janbu, Bishop, Spencer and etc.) based on selected values in step 1.
3. Repeating steps 1 and 2 for many times as necessary.
4. Determining distribution function of factors of safety and probability of failure.

In the present paper, it is tried to illustrate the application of Monte Carlo method to analyze the slope stability of an earth dam. In this respect, upstream slope of Doosti dam located in Iran has been considered as a case study. The analysis has been accomplished using Mohr-Coulomb constitutive model by SLOPE/W software, version 6.02. Bishop, Janbu and Spencer methods are employed to compute the reliability index of upstream slope of dam with respect to uncertainties of strength parameters of construction materials.

2. *Assumptions of Slope Stability Analysis in Bishop, Janbu and Spencer Methods*

In this paper, three different deterministic analysis methods have been used in Monte Carlo simulation to perceive a comparison between their results.

Several assumptions were made in simplified Bishop method (Bishop, 1955; Anderson and Richards, 1987):

1. The failure is assumed to occur by rotation of a mass of soil on a circular slip surface centered on a common point.
2. The forces on the sides of the slice are assumed to be horizontal. Thus, there is no shear stress between slices.
3. The total normal force is assumed to act at the center of the base of each slice.

Although, simplified Bishop method does not satisfy equilibrium, but safety factors derived from this method is in agreement with the safety factors calculated from finite element methods (Wright et al., 1973).

In simplified Janbu method, the assumption of inter-slice shear forces equal to zero doesn't satisfy moment equilibrium. However, Janbu defined a correction factor (f_0) which is a function of slide geometry and strength parameters of soil. Applying Janbu method to the non-circular slip surfaces is the advantage of this method (Janbu, 1968).

Spencer (1967) developed a method satisfying static equilibrium accurately. In this method it is assumed that the inter-slice forces are parallel so they have the same inclinations. Spencer's method was presented originally for the analysis of circular slip surfaces, but it is extended to non-circular slip surfaces by adopting a frictional center of rotation (Spencer, 1967; Albataineh, 2006).

3. *Risk Analysis on Upstream Slope of Doosti Dam*

Doosti Dam was constructed on Harirud River between the border of Iran and Turkmenistan. The specifications of Doosti dam are represented in Table 1.

Table 1: Doosti dam specifications (Toossab Consulting Engineers Company, 2000b)

Dam type	Earth and rockfill dam with silty clay core	Crest length	655 m
Height	79 m above its rock foundation	Dam width	428 m
Reservoir max. elev.	76.5 m above foundation	Reservoir total volume	1250 hm^3

Figure 1 shows the cross section of Doosti dam. Geotechnical parameters of foundation and embankment are given in Table 2 (Toossab Consulting Engineers Company, 2000a; b; c; U.S. Army Corps of Engineers, 2006).

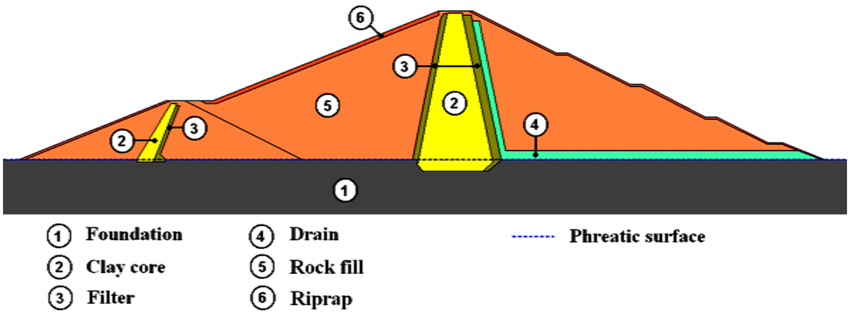


Fig. 1: Cross section Doosti dam

Table 2: Geotechnical parameters of Doosti dam

	Average	Coefficient of variation [%]	Standard deviation	Average	Coefficient of variation [%]	Standard deviation
	Foundation			Clay core		
Moist unit weight [kN/m^3]	26	3	0.78	18.5	3	0.56
Saturated unit weight [kN/m^3]	26.5	3	0.8	19.5	3	0.59
Internal friction angle [°]	24.3	10	2.43	6.5	10	0.65
Cohesion [kN/m^2]	48	40	19.2	85	40	34
	Filter			Drain		
Moist unit weight [kN/m^3]	19.5	3	0.59	19.5	3	0.59
Saturated unit weight [kN/m^3]	20.5	3	0.62	20.5	3	0.62
Internal friction angle [°]	27	12.61	3.41	34	10	3.4
Cohesion [kN/m^2]	17.5	39.37	6.89	0	-	-
	Rock fill			Riprap		
Moist unit weight [kN/m^3]	21	3	0.63	21.5	3	0.65
Saturated unit weight [kN/m^3]	22	3	0.66	22.5	3	0.68
Internal friction angle [°]	37.2	10	3.72	43	10	4.3
Cohesion [kN/m^2]	0	-	-	0	-	-

According to Monte Carlo simulation method, a random value has been selected for each input parameter based on the assigned probability density function and its amplitude.

Theoretically, the more Monte Carlo trials the more accurate the solution will be, but the number of required Monte Carlo trials is dependent on the level of confidence in the solution and the amount of variables being considered. Statistically, the following equation has been recommended (Krahn, 2004):

$$N = \left(\frac{d^2}{4(1-\varepsilon)^2}\right)^{\mathrm{m}} \quad (1)$$

where: N= number of Monte Carlo trials, d= the normal standard deviation corresponding to the level of confidence, ε= desired level of confidence, and m= number of variables. Table 3 represents some confidence level (ε) with their relevant standard deviation (d).

Table 3: Standard deviations according to Confidence levels

Confidence level (ε)	Standard deviation (d)
80%	1.282
90%	1.645
95%	1.960
99%	2.576

Based on Equation 1, the average values assigned for unit weights of all materials due to their small coefficient of variations, and all parameters of riprap and drain due to their low thickness and their small length along slip surface have been considered. In this study, 115000 trials have been done with respect to standard deviation of 1.282 and confidence level of 80%. Figure 2 shows the probability distribution of materials used in Doosti dam analysis.

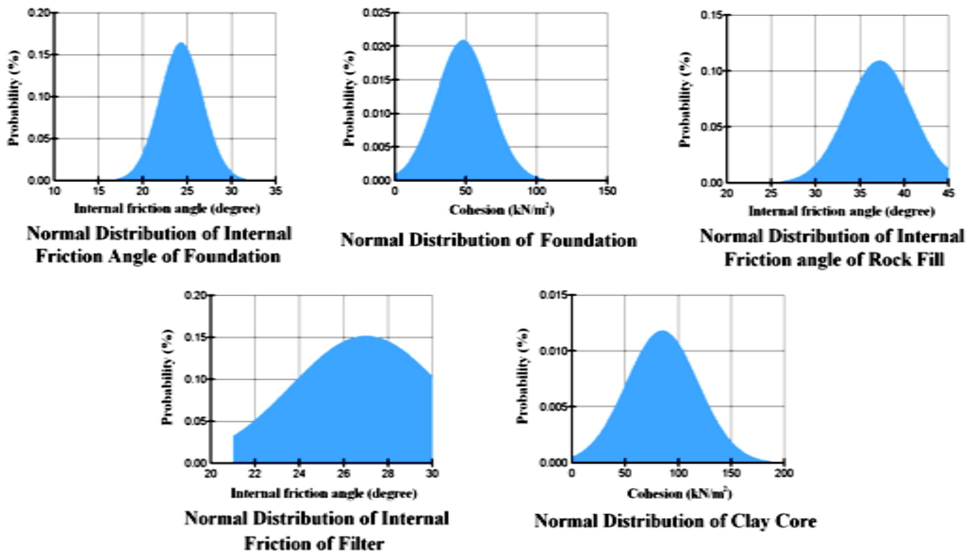


Fig. 2: Probability distribution of materials used in Doosti dam analysis

More than 1300 slip surfaces have been checked and the most critical deterministic slip surface of each method has been chosen to study the probabilistic analysis of slope stability. Figures 3 to 5 displays the critical slip surface of each method. The safety factor of 1 has been characterized for the critical safety factor of analysis as is common in geotechnical engineering practice. It is worthy to remind that in the present research only slope instability is considered.

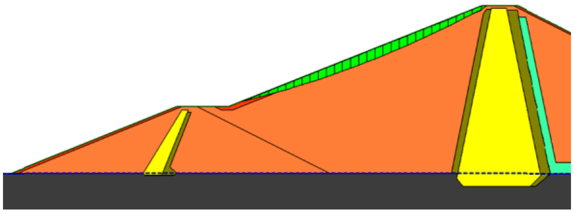


Fig. 3: Upstream critical slip surface of Bishop method

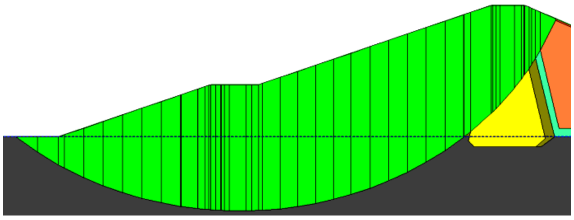


Fig. 4: Upstream critical slip surface of Janbu method

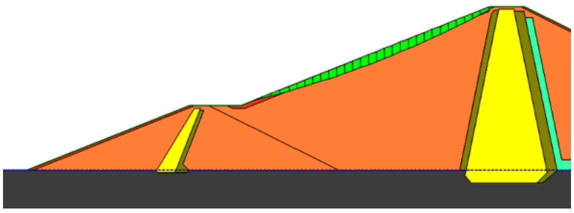


Fig. 5: Upstream critical slip surface of Spencer method

Reliability index is a rational probabilistic criterion for safety level which can be calculated by the following equation:

$$\beta = \frac{E[FS] - 1}{\sigma[FS]} \tag{2}$$

where: $E[FS]$ and $\sigma[FS]$ are average and standard deviation of safety factors respectively. Reliability index represents the level of reliability of an engineering system and reflects the effects of uncertain parameters on probabilistic analysis.

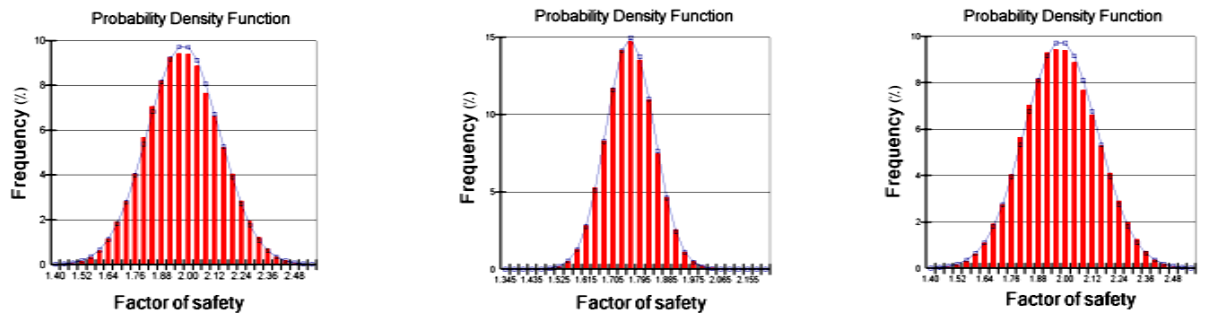
The results of deterministic and probabilistic slope stability analysis of upstream slope of Doosti dam in condition of after dam completion are represented in Table 4.

Table 4: Results of deterministic and probabilistic slope stability analysis

Upstream Slope		Slope Stability Analysis Method		
		Bishop	**Janbu**	**Spencer**
Deterministic Analysis	Total Activating Force [kN]	-	80128	2814.7
	Total Activating Moment [kN.m]	1457500	-	1457500
	Total Resisting Force [kN]	-	141070	5565.5
	Total Resisting Moment [kN.m]	2885900	-	2886500
	Deterministic Factor of Safety	1.98	1.7605	1.9805

Probabilistic Analysis	Number of Trials	115000	115000	115000
	Min. Factor of Safety	1.382	1.4482	1.3872
	Max. Factor of Safety	2.54	2.1258	2.5393
	Mean Factor of Safety	1.9785	1.7622	1.98
	Standard Deviation	0.163	0.08	0.163
	P (Failure) (%)	0	0	0
	Reliability Index	5.991	9.523	6.009

The probability density functions of safety factors of each method are given in Figure 6 while Figure 7 illustrates the diagrams of deterministic safety factors and reliability index of each method.



Safety factors probability density function of Bishop Method **Safety factors probability density function of Janbu Method** **Safety factors probability density function of Spencer method**

Fig. 6: Safety factors probability density functions of Bishop, Janbu and Spencer methods

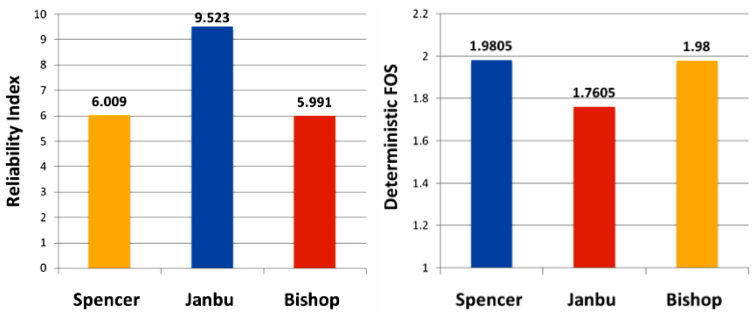


Fig. 7: Deterministic safety factors and reliability index of selected methods

The results indicate that Bishop method with reliability index of 5.991 has the lowest reliability index among selected methods. According to U.S. Army Corps of Engineers (2006), for embankment dams, slopes with reliability index of more than 3 are stable. As it appears from Figure 7, although Janbu method has the lowest deterministic safety factor among selected methods, but indicates the highest reliability index. Lower standard deviation of safety factors of Janbu method is the reason of this fact. The result shows the inability of deterministic analysis to determine accurate risk level.

It is important to keep in mind that the most critical slip surface derived from deterministic analysis is not necessarily the most critical slip surface of probabilistic analysis, but it is an appropriate estimation of critical slip surface of probabilistic analysis.

4. Conclusion

The studies on slope stability analysis specify that safety factor of deterministic analysis is not a comprehensive criterion for determining of dam safety level. Rather, it is necessary to utilize risk based analysis too. This paper has been focused the importance of risk analysis application in the analysis of embankment dams. In this respect, utilization of Monte Carlo simulation method has been presented for a case study. In this study, the reliability index of upstream slope of Doosti dam has been calculated with three different analysis methods of Bishop, Janbu and Spencer. The results ensure the stability of selected slope.

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