Reliability Analysis of Earth Dam: Case of Kalan Earth Dam – Malayer, Iran

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Abstract
Slope stability assessment is a geotechnical problem characterized by many sources of uncertainty. Beginning from a correct geotechnical characterization of the examined site, only a complete approach to uncertainty matter can lead to a significant result. Factors of safety (FS) provide a quantitative indication of slope stability which should be determined by experience and the degree of uncertainty that we think is involved in calculating FS. The reliability index of an earth dam in commonly taken as the value corresponding to the failure surface associated with minimum reliability index. However, embankment dams are considered as systems composed of several infinite number of possible failure surfaces associated with different reliability indices. In this paper, the reliability analysis has been performed on Kalan embankment dam of Malayer, Iran by a numerical procedure for locating the surface of minimum reliability index for the earth slope. Here, basic assumption, which considers soil properties of the embankment dam are statistically homogeneous, has been followed.

Keywords: *Earth Dam, Reliability Index, Factor of Safety, Slope Stability, Failure Probability*

1. Introduction
There have been numerous attempts in recent years to use a probabilistic approach complementary to the conventional approach for analyzing the safety of slopes. The conventional deterministic approach is based on minimizing the factor of safety (FS) over a range of candidate failure surfaces thereby determining the surface of minimum factor of safety, referred to as the critical deterministic surface. A common approach to determine the reliability of a slope is based on calculating the reliability index β corresponding to this surface.

Probabilistic analyses have also been performed on arbitrary slip surfaces. Parametric studies have been conducted considering different specified surfaces not necessarily associated with the minimum factor of safety or minimum reliability index [1, 2]. Li and Lumb [3] located the critical deterministic surface and then used it as the initial trial surface to search for the surface of minimum β, referred to as the critical probabilistic surface. The geotechnical engineering designer has to provide a way to systematically incorporate uncertainty into the design process in a rational manner and to must take it into account the soil variability and optimize design [4-8].

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Within the literature, there is a multitude reliability analyses can be used in routine geotechnical engineering practice. How should probabilistic methods be introduced to practicing geotechnical engineers who have no background in the probabilistic theory? These simple reliability analyses require a little effort more that involved in conventional geotechnical analyses [9]. As interest in probabilistic approach of slope stability analysis increases, there is growing need for algorithms to search for the minimum β surface. It is now recognized [10] that the search for the minimum β surface in the probabilistic approach is similar in principle to that for the minimum FS surface in the deterministic approach.

2. Reliability Analysis

Reliability analysis plays a major role in considering the uncertainties influencing the design of earth structures. Any simple reliability analysis should include the following steps: Establishing limit states, identifying failure modes, formulating limit state functions, analyzing uncertainty, evaluating reliability and Assessment results [9].

The conventional factor of safety is defined as the ratio of limit capacity of soil to a demand in terms of loads:

$$F = \frac{R}{S} \tag{1}$$

in which R = capacity (resisting force or resisting moment); and S = demand (driving force or driving moment). Let $f_R(r)$ and $f_S(s)$ be the probability densities functions of variables R and S. The probabilistic measure of safety is the probability of failure, P_f in which should be smaller than certain reference values set a priori.

The probability of failure is defined as (failure occurs if R<S):

$$P_f = P(\frac{R}{S} \leq 1) \tag{2}$$

Assuming statistical independence between the variable R and S the probability of failure can be expressed as:

$$P_f = \int_{-\infty}^{+\infty} f_s(s)(\int_{-\infty}^{r=s} f_R(r)dr))ds \tag{3}$$

The use of later formulation of probability of failure makes the simplification possible only for certain types of distribution of R and S such a normal distribution. In such case the notion of safety margin, MS=R-S, can be introduced [6]. It is Possible to derive the density function $f_{MS}(MS)$ of the random variable MS and the risk of failure is given as:

$$P_f = \int_{-\infty}^{0} f_{MS}(MS)d(ms) \tag{4}$$

In general, the calculus of the integrals in the preceding equations is particularly cumbersome. In this case, safety is defined by the reliability index, β, as [10]:

$$\beta = \frac{E\{MS\}}{\sigma_{MS}} \tag{5}$$

in which E{MS} = expected value of MS; and σ_{MS} = standard deviation of MS, provides a simple quantitative basis for assessing risk i.e. probability of failure.

3. Case Study

3.1. Description and Presentation of Kalan Dam

Kalan earth dam (West of Iran) is selected as a case study to perform the reliability analysis. Its reservoir is a man made water body built on Marvil, 30 km south of Malayer, for farming and water supply purposes. The hydraulic characteristics of the dam are shown in Table 1.
Kalan dam has a height of 47 m and crest width of 10 m. Maximum water height back of the upstream shoulder is 45 m. The outer slopes of the dam are made of 1V: 4H upstream shoulder and 1V: 3.5H the downstream shoulder respectively (Figure 1).

3.2. Properties of the Dam and Foundation Materials

The compacted materials were evaluated according to their maximum dry unit weight (γ_{dmax}), optimum water content (w_{opt}), specific gravity (γ_s), liquid limit (LL) and plasticity index (I_p). The construction material for embankment and foundation were: Material A- Filter zone: granular material, Material B- downstream shoulder zone: granular material and clay with medium plasticity and Material C- soil foundation and upstream shoulder zones: clay with medium plasticity. The main physical and shear strength parameters are reported in Table 2.

3.3.Performance and Analysis of Kalan Dam

The stability analysis of Kalan embankment dam and its foundation is carried out using a deterministic approach. The limit equilibrium Slide ver.5 program is used. Different modes of failures are implemented in Slide ver.5 program which provides a choice of methods of analysis including the following: Bishop's method, Lowe-Karafiath's method, Spencer's method and Janbu's method.
The former method has been selected to evaluate the safety factor. A minimum factor of safety (FS) of 1.46 for ellipsoid failure mechanism has been found. An example of Slide program analyses of Kalan dam is shown in figure 2. Subsequently, for the reliability analysis of Kalan dam, only the ellipsoid failure mechanism will be considered.

4. Reliability Analysis of Kalan Dam

Recently, special attention has given to the role of spatial correlation. Some recent papers dealing with the concept include those by Mrabet and Giles [6]. Many studies stressed out the effect of existing auto-correlation on the results of probabilistic models of compacted earth slopes analysis. Similar pattern have been found for mechanical properties and the exponential auto-correlation function between two different points within the compacted soil of the Kalan dam has been retained. Due to the lack of data concerning the horizontal auto-correlation function, we were reported to Anderson’s work [11] to establish one. We therefore, obtained the following function:

$$\rho_{hor9x} = \exp(-0.065x) \quad (6)$$

In this article at first groundwater analysis has been done by finite element method then the calculated probability associated to the critical failure surface constitutes a lower limit of the global probability of failure of Kalan dam. Subsequently, we calculate the global probability of failure in respect to the following condition:
-Cross-section of Kalan dam as considered in the above analysis (figure 1).

-Horizontal auto-correlation distance is: 60 m
-Vertical auto-correlation distance is: 5 m
-Coefficient of variation of the cohesion of the Kalan dam is: 1
The global failure probability is calculated using the following equation:

$$P_{global} = 1 - \prod_{i=1}^{n} (1 - P_{fi}) \quad (7)$$

Where P_{fi} is failure probability corresponding to the ellipsoid failure surface i. The global probability of failure is P = 0.015. This value is close to the value associated with the critical ellipsoid failure surface. This calculation shows that the concept of global probability is coherent; should be considered, later, as the global probability of the project.
In reality, these results show that other sources of uncertainty that should be taken into account including, but not limited to: 1. Ignorance of mechanisms of failure; 2. Ignorance of the entire history of dam behavior and 3. Ignorance of the horizontal auto-correlation length.

5. Conclusions

The present study has been oriented to provide and compare useful model application results to a slope stability reliability analysis. Although this model is greatly used and diffused, some aspects connected to their application should be further investigated. Such aspects (e.g. the search for the most critical probabilistic surface, β_{min} calculation, data uncertainty propagation and modelling) play an essential role for a good quality solution. However, the reliability analysis should be considered as an efficient tool that complemented a conventional deterministic analysis such as the equilibrium limit analysis. Also The global probability of failure value is close to the value associated with the critical ellipsoid failure surface.
Particularly, correlations between different properties that characterize compacted materials and their corresponding horizontal auto-correlation lengths generate main uncertainties in the probabilistic model. The application of a simple algorithm with a correct experienced-based parameter definition provides results that are in good agreement, mentioned slope stability solutions, in terms of reliability index and probability of failure. This seems to encourage the application of similar uncertainty treatment to the slope stability assessment.

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Table 1. Hydraulic characteristics of Kalan dam

Area of basin pouring	384 km^2
Total capacity	45×10^6 m^3
Yearly average contribution	35×10^6 m^3

Table 2. Physical properties and shear strength parameters

Materials Properties	A	B	C
W_L (%)	-	25	39
I_P (%)	-	15	22
W (%)	-	13	14.5
γ_d/γ_w	-	1.5	1.83
φ (degree)	35	22	26
c (kPa)	0	8.5	11

c = cohesive strength, φ = friction

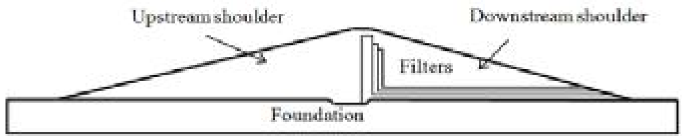

Figure 1. General cross section schematic of Kalan dam.

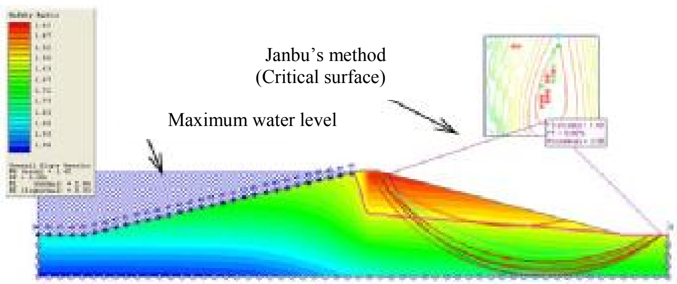

Figure 2. Analysis of downstream slope of Kalan dam using limit equilibrium to find the ellipsoid failure surface (Janbo's simplified method, Slide 5)