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# Statistics for the calculated safety factors of undrained failure slopes

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ABSTRACT

Due to the uncertainty and variability involved in ground conditions and analytical methods, the calculated factor of safety (FS) of a slope may not be exact. To know whether the calculated FS is unbiased and also the magnitude of its variability, this paper re-analyzes 43 real cases of undrained slope failure reported in the literature. The FS is re-calculated using two-dimensional (2-D) limit equilibrium methods (LEM) (i.e., the simplified Bishop's method and the Spencer's method) to minimize the human factor in FS calculation. Since all cases failed, the conditions (such as geometries) right before failures were adopted to simulate the nearly failure condition in the LEM. Based on the statistical results of the calculated FS obtained from hypothesis testing, it can be concluded that (a) the 2-D LEM seems to give unbiased FS estimates; (b) the FS variability for natural slopes is significantly larger than that for man-made slopes; (c) the conversion of the undrained shear strength ($s_u$) to its field value is the most crucial, and the modeling of $s_u$ spatial variability is also crucial; and (d) the standard deviation of the human error in the logarithm of the calculated FS is about 0.25, and the human error appears to be uncorrelated to the logarithm of the calculated FS. Finally, the relationship between the failure probability of a man-made undrained clay slope and its calculated FS is developed to facilitate reliability analysis and reliability-based design.

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## 1. Introduction

Factor of safety (FS) is commonly used to quantify the safety level of a slope. Due to the uncertainty and variability involved in ground conditions and analytical methods, the calculated FS of a slope may not be exact. To address the uncertainty and variability, reliability analysis and reliability-based design of a slope have become the research subjects with growing interest. In literature, the reliability analysis and reliability-based design for a slope were carried out by using expert judgment (Lambe, 1985; Silva et al., 2008) or analysis/simulation method (Chowdhury and Xu, 1993; Christian et al., 1994; Low et al., 1998; Griffiths and Fenton, 2004; Ching et al., 2009; Huang et al., 2010; Jha and Ching, 2013; Wang et al., 2013; Zhang et al., 2013).

This study focuses on a more fundamental issue: the accuracy of the calculated FS (i.e., is it unbiased? or what is the magnitude of the variability?). This paper re-analyzes 43 cases of slope failures in clays documented in the literature: 27 embankments (fill slopes), 7 excavations (cut slopes), and 9 natural slopes. The factors of safety of these 43 cases are re-calculated using two-dimensional (2-D) limit equilibrium methods (LEMs): the simplified Bishop's method (Bishop, 1955) and the Spencer's method (Spencer, 1967). Since all these 43 slopes failed, the geometry conditions (such as embankment heights) right before failure are adopted to simulate the nearly failure cases in the LEM analysis. The purpose of the paper is to address the following questions:

1. Is the factor of safety (FS) calculated by 2-D LEM for a nearly failure slope indeed close to 1? How large are the bias (with respect to 1) and variability? Do such bias and variability depend on the types of the slope (fill, cut, or natural)?
2. How large is the man-made error in the calculated FS? What happens if a slope is analyzed in a less strict manner (i.e., considering fewer factors)?

The above questions are to be answered by hypothesis testing based on the statistics of the calculated FSs.

A similar study has been recently taken by Travis et al. (2010), where the FSs of 301 failure cases were collected directly from literature, but none of these cases was re-analyzed. Since the 301 cases were studied by different researchers, some were analyzed using methods assuming circular failure surfaces, but some were not; some were based on total stress analysis, but some were based on effective stress analysis. In addition, the undrained shear strengths ($s_u$) were determined in different ways, some based on unconfined compression test (UC) and some based on field vane test (FV). A similar effort was also taken by Wu (2009). Eight failure slope cases were collected, but only one case was re-analyzed. In comparison, the 43 cases studied in this paper are re-analyzed to minimize the FS variability due to man-made calculation.

Based on the results of the statistical analysis on the calculated FS, a simplified relationship between the failure probability of a man-made

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undrained clay slope and its calculated FS will be developed to facilitate reliability analysis and reliability-based design.

## 2. Case histories

Case histories of slope failures are collected from literature in the period from 1956 to 2002 (Table 1). Among them, 27 are embankments (fill slopes), 7 are excavations (cut slopes), and 9 are natural slopes. Site locations widely spread from Europe, US, South America, Arabian Gulf to Asia. Slope heights range from 2 to 34 m, and slope angles range from 14 to 53°. The observed failure surfaces are mostly circular. The subsoil materials are mostly silty clays, with unit weights ranging from 11 to 20 kN/m$^3$ and plasticity indices ranging from 8 to 70. The most common tests used to determine the undrained shear strengths ($s_u$) of the clays are field vane (FV) test and unconfined compression (UC) test. The embankment fills are typically sandy or silty soils. Most of the cut slopes and fill slopes are parts of road facilities, but some fill slopes are test embankments that were built to fail. For the cut and fill slopes, the clay layers are mostly fully saturated. For cut slopes, all soil layers are below the original ground surface, hence they are considered fully saturated if they are below the original water table in the ground. For fill slopes, clay layers are beneath the fill and are considered fully saturated. For natural slopes, there is typically insufficient information in literature to conclude whether the clay layers are saturated or not.

The FSs calculated in the literature are listed in Table 1 (column 10). But the analysis procedures for these FSs are not uniform. For instance, most cases were analyzed without the conversion of the undrained shear strength with respect to stress state, sample disturbance, and strain rate effect, but there are exceptions (cases 16, 32, 33, and 40). Also, the analysis methods are not consistent: 23 cases were analyzed by the Swedish circle method (the $\phi = 0$ method), 15 cases by the simplified Bishop's method, and 1 case by the Janbu's method, and 1 case by the modified Fellenious' method. There are occasions where a single case has more than a single FS. This can happen if the case was studied by more than one reference or the case was analyzed using more than one calculation method. For such cases, Table 1 only shows the smallest FS.

## 3. LEM analysis procedures in this study

Two LEMs, the simplified Bishop's and the Spencer's methods, are adopted to calculate the FSs of the 43 cases. All cases are nearly failure cases. For each case, the LEM analysis uses the 2-D slope geometry right before failure. For instance, an embankment (fill slope) built in several stages had a total design height of 10 m, but it failed at the fourth stage with a height of 7 m. Then, 7 m is taken to be the slope height rather than 10 m in the LEM. To make the LEM as accurate as possible, the following three procedures (P1, P2, and P3) are taken:

1. Conversion of undrained shear strength (P1)
The undrained shear strengths ($s_u$) for the 43 cases are obtained from UC and FV tests. In principle, the UC and FV values should not be directly used as the input parameter to the LEM because the strain rates and stress states of UC and FV tests are different from the field strain rates and stress states which occurred during the failures of the slopes. So, they are converted into the “field” values in this study. Mesri and Huvaj (2007) proposed that for the UC tests,
$$s_u(\text{field}) \approx s_u(\text{UC}) \tag{1}$$
whereas Bjerrum (1972) proposed that for FV tests,
$$s_u(\text{field}) \approx s_u(\text{FV}) \times \mu \tag{2}$$
where $\mu$ is a correction factor that depends on plasticity index (PI). For a case history where both UC and FV tests are conducted, FV values are adopted and Eq. (2) was adopted, because FV has less variability than UC (Phoon and Kulhawy, 1999). Embankment fills are typically sandy or silty soils. The more relevant parameter is the effective friction angle $\phi'$. The $\phi'$ values for the fill materials in fill slopes are listed in Table 1. Most of these $\phi'$ values are documented in the literature. There are four cases where the $\phi'$ values are unknown. For these cases, $\phi' = 35°$ is assumed.
2. Detailed modeling of spatial variability of $s_u$ (P2)
It is known that $s_u$ may be spatially variable because it is strongly correlated to effective overburden stress and overconsolidation ratio. In particular, there may be a dry crust near the ground surface where the $s_u$ value is higher than normal. In this study, the spatially variable $s_u$ is modeled by adopting thin clay layers in the LEM analysis. The $s_u$ value in each layer conforms to the $s_u$(field) profile, converted from the $s_u$ profile available from the literature.
3. Modeling of tension crack (P3)
Significance of applying tension crack in LEM is debatable. Some studies suggested that the effect of tension crack can be neglected (e.g., Spencer, 1973), whereas some others showed that ignoring tension zones may lead to overestimation in the FS (e.g., Duncan and Wright, 2005; Chowdhury et al., 2010). In this study, tension crack is adopted in LEM by checking the normal force at the base of first slice in the slope crest. If it is positive, the calculation continues, but if it is negative, the slice will be removed and FS is recalculated. This process is repeated until there is no negative normal force at the base of the remaining first slice. This procedure is similar to the automatic tension crack search procedure used in SLOPE/W (Krahn, 2004).

The factor of safety of a trial slip surface is calculated by methods of slices. For circular slip surfaces, the simplified Bishop's method is used. For non-circular slip surfaces, the Spencer's method is used. The assumptions for these two LEM methods are shown in Table 2. Forty slices are used in both methods. For the Spencer's method, 7 vertices are used for the non-circular slip surfaces. This number of vertices performs reasonably well, as shown in Greco (1996). For both methods, the search of the most critical slip surface requires a robust optimization algorithm to locate the slip surface with the minimum factor of safety. Robustness means that different realizations of the optimization solutions are identical. The heuristic global optimization technique CoDE developed by Wang et al. (2011) is found to be fairly robust. Procedures developed in Cheng (2003) are adopted to generate circular and non-circular trial slip surfaces. The CoDE algorithm is allowed to explore 60,000 trials in total. The number of trials (=60,000) is found to be adequate to assure convergence.

Using Case 1 (Nesset) as an example. It is a fill slope (embankment) case. The profile for this case (including the fill) is shown in Fig. 1a. The ground level is at the elevation of 10 m. The fill is with height = 3 m right before the failure, so the top of the fill is at the elevation of 13 m. The undrained shear strength ($s_u$) and unit weight ($\gamma$) for the clay below the ground level is shown in Fig. 1b. This figure is redrawn from Fig. 3b in Flaate and Preber (1974). The undrained shear strength was from the UC tests, so Eq. (1) is used to compute the field value $s_u$(field). A dry crust is absent for this particular case. Based on the borehole profile in Fig. 1b, the clay below the ground level is divided into 5 layers to model the spatial variability of $s_u$. The adopted $s_u$ values for these 5 layers are shown in Fig. 1a. These values are also shown as the vertical dashed lines in Fig. 1b. Tension crack is also considered in the LEM. For this particular case, the simplified Bishop's method gives FS = 0.98 and the Spencer's method gives FS = 0.94. The critical slip curves obtained by the CoDE algorithm are both shown in Fig. 1a.

## 4. Analysis results

The calculated FSs for all cases are presented in Table 3. The “All” columns (columns 3 & 4) mean that all three procedures P1, P2, and P3 are adopted. The sample mean and sample standard deviation of the FSs are listed at the bottom of the table. It is worth highlighting

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