Assessing the Stability of Poor Drainage Soil Slopes Under the Combined Effect of Water Level Drawdown and Rainfall

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Abstract. In rainy season, the reservoir water level sometimes decreases greatly for the requirement of flood discharge. Such phenomenon may cause severe landslides for poor drainage soil slopes. Therefore, it’s necessary to assess the slope stability under the combined effect of rainfall and water level drawdown. In this study, a homogeneous soil slope was modelled to investigate the relative importance and failure mechanism of water level drawdown and rainfall. Both the “factor of safety” (FOS) and the “probability of failure” (POF) were computed in the analysis. The numerical results show that landslides are more susceptible to water level drawdown, while rainfall is a secondary influence to poor drainage soil slopes, subjected to the combined effect of water level drawdown and rainfall.

1. Introduction
The analysis of slope safety is one of the main issues in geotechnical engineering. In recent years, probabilistic methods have been more and more widely used since such analysis can reveal more details compared with traditional safety factor methods. This paper will simulate a typical homogeneous soil slope in reservoir areas and discusses the numerical results based on the “factor of safety” (FOS) and the “probability of failure” (POF). The combined effect of rainfall and water level drawdown is taken into consideration to reveal the relative importance and failure mechanism of each influential factor. The research is carried out through one group of parametric study, where rainfall intensity and drawdown speed in water level are varied.

2. Methodology
The numerical simulation of the soil slope is based on one group of parametric study, including three main parts: (1) choosing appropriate values for influence factors; (2) seepage analysis; (3) slope stability analysis.

2.1. Designing parametric study
Figure 1 shows the geometry characteristics and the hydrogeological properties of the homogeneous soil slope, which will be analyzed in this paper. Rahardjo et al. (2007) proposed that the slope geometry and the initial water table location have secondary effects on slope stability. Therefore, the slope geometrical
Figure 1. Geometry characteristics and hydrogeological properties of the homogeneous soil slope analyzed in parametric studies

conditions are taken as deterministic here: slope height \( H_s = 20 \text{ m} \), slope angle \( \alpha = 33.7^\circ \). The selection of geometry characteristics for the soil slope is based on the works of Liang (2013), who carried out a representative model test in Three Gorges Regions (TGR).

The combinations of influential factors affecting slope stability are shown in Table 1. The soil type used in this paper is based on the works of Huang et al. (2016), who analyzed the effect of permeability coefficients on slope stability. The symbol S represents soil and the subscript means the saturated permeability coefficient \( k_s = 10^{-6} \text{ m/s} \), widely considered as a boundary of poor drainage soils.

The rainfall intensity (40 and 360 mm/d) selected in the parametric study is according to the classification of China Meteorological Administration (CMA), who suggested the respective boundary of moderate rain and extraordinary rainstorm. All the rainfalls applied to the soil slope are assumed to last as a short duration (3 days here).

Gao et al. (2018) indicated that the water level drawdown speed was approximately 1.0-2.0 m/d. However, a lower velocity of water level fluctuation does exist in some cases. Therefore, the water level decreases at speeds of 0.5, 1.0 and 2.0 m/d in this work, and the corresponding durations are 20 days, 10 days and 5 days, respectively, from 34 m to 24 m.

In probabilistic slope stability analysis, the shear strength parameters of soils are considered as variables: cohesion \( c' = 24 \text{ kPa} \) and friction angle \( \phi' = 23^\circ \), with a standard deviation of 2.4 and 2.3, respectively. It is assumed that there is no correlation relationship between the two variables and they all are normally distributed. The unit weight of soils is kept as a constant, \( \gamma = 20 \text{ kN/m}^3 \).

2.2. Seepage Analysis

As mentioned previously, the seepage analysis was performed after selecting appropriate values for influential factors. Then, the computed results of seepage analysis were utilized for subsequent slope stability analysis. In this paper, both seepage analysis and stability analysis were performed by the commercial program Slide v.8 (Rocscience Inc. 2018). For seepage analysis, it’s of great significance to set appropriate soil-water characteristic curve (SWCC) and hydraulic conductivity function (HCF).

The model proposed by Fredlund and Xing (1994) was utilized to describe the SWCC for soils in this section. The equation is as follows:
\[ \theta = C(\psi)\theta_s \left[ \frac{1}{\ln(e + (\psi/a)^n)} \right]^m \]  

(1)

In above equation, \( C(\psi) \) is a correction function defined as:

\[ C(\psi) = \left[ 1 - \frac{\ln(1 + \psi/\psi_r)}{\ln(1 + 10^6/\psi_r)} \right] \]  

(2)

where \( \theta \) = volumetric water content; \( \theta_s \) = saturated volumetric water content; \( \psi \) = the matric suction; \( e \) = the base of the natural logarithm (2.71828); \( a, n, m \) = curve fitting parameters; \( \psi_r \) = the suction when soil is at the residual condition (kPa); \( \psi \) = the matric suction (kPa).

The HCF of soils can be described through the equation proposed by Leong and Rahardjo (1997):

\[ k = k_s \left[ \frac{1}{\ln \left( e^{+(\phi/A)} \right)} \right]^c \]  

(3)

where \( \psi \) = the matric suction (kPa); \( k_s \) = saturated permeability coefficient; \( k \) = permeability coefficient; \( A, B, C \) = fitting parameters (similar but different as the parameters in SWCC). In Slide v.8, the fitting parameters defined in permeability functions can be automatically used to describe the SWCC of soils. And based on the cases analyzed by Leong and Rahardjo (1997), the values of “Yolo light clay” were adopted in this paper (\( A=4 \) kPa, \( B=1 \) and \( C=6 \)). The limit of negative pore-water pressure was selected as -75 kPa to avoid unrealistic situations.

2.3. Stability analysis

Considering the effect of matric suction, the governing equation for unsaturated shear strength is as follows (Vanapalli et al. 1996):

\[ s = c' + (\sigma_n - u_a) \tan \phi' + (u_p - u_w) \left[ \left( \frac{\theta_t - \theta_r}{\theta_t - \theta_u} \right) \tan \phi' \right] \]  

(4)

where \( s \) = shear strength of unsaturated soil; \( c' \) = effective cohesion; \( \sigma_n \) = total normal stress; \( u_a \) = pore-air pressure; \( u_p \) = pore-water pressure; \( \sigma_n - u_a \) = net normal stress; \( u_p - u_w \) = matric suction; \( \phi' \) = effective angle of internal friction; \( \theta_t \) = the volumetric water content (VWC); \( \theta_s \) = the saturated VWC; \( \theta_r \) = the residual VWC where soil suction strength is zero. In the parametric study, both \( \theta_t \) and \( \theta_r \) were regarded as constants as 0.4 and 0.05, respectively.

Slope stability problems are widely analyzed by traditional limit equilibrium methods (LEMs). The approach used here is Morgenstern-Price (M-P) method since it’s accurate and applicable to the failure surface.

2.4. Probabilistic analysis for slope stability

Considering that one-point statistical parameters of properties (i.e., the mean and variance) can hardly reflect the realistic features of soils. Besides, the inherent spatial variability has been revealed and analyzed by many researchers. (Griffiths et al. 2001; Elkateb et al. 2003). Vanmarcke (1983) proposed that spatial variability of soils can be effectively described by their correlation in random fields. Therefore, the random field considering spatial soil variability was utilized in this section.

The element in random field analysis is determining the correlation distance, defined to reflect the variation of soil properties. Griffiths and Fenton (2000) proposed that the worst spatial correlation length, leading to a maximum POF, ranges from 0.5 \( H_s \) to 1 \( H_s \), where \( H_s \) is the slope height. In addition, Cho (2010) suggested that correlations in the vertical direction have much shorter lengths than those in the horizontal direction. Therefore, the correlation distances in vertical direction (Y direction) and horizontal direction (X direction) were selected as 5 m and 20 m, respectively.
The random field method involves a Monte Carlo simulation with many trials to compute a POF. Therefore, it’s of importance to ensure an appropriate number of trials, which provide accurate results and avoid excess computational efforts. The default sampling method in *Slide* is Latin Hypercube Sampling, resulting in a smoother and more uniform sampling. According to the program, a probabilistic analysis using 1000 samples obtained by such sampling method is applicable and accurate enough.

The model considering spatial variabilities of soil properties is shown in Fig. 2 and Fig. 3, where the elements with warmer color represent lower shear strength.

![Figure 2. Slope model considering the spatial variability of cohesion](image1)

![Figure 3. Slope model considering the spatial variability of phi](image2)

### 3. Results and discussion

The results of the parametric study are shown in this section with focuses on the influential factors of rainfall intensity and water level drawdown speed. Figs. 4a1, 4a2 and 4a3 show the variations in FOS with time when the reservoir water level decreases at speeds of 0.5, 1.0 and 2.0 m/d, respectively. A comparison of all the plots in Fig. 4 indicates that the minimum FOS occurs at the end of water level drawdown, 20 days, 10 days and 5 days, respectively. Fig. 4 shows that the higher water drawdown speed the faster and steeper FOS decreases with time. Besides, it also shows that the differences among the scenarios with diverse rainfall intensity but same drawdown speed are less obvious. These observations indicate that the stability of poor drainage soil slopes is mainly controlled by water level drawdown and less affected by rainfall.

![Figure 4. The variations of FOS with time (a1-a3) water level drawdown speed: 0.5, 1.0 and 2.0 m/d](image3)

The similar observations can also be found in Fig. 5, where the variations in POF with time were presented. In order to better compare the results, according to the size of failure probabilities, the stability of landslides can be divided into five levels, as shown in Table 2.

| Failure probabilities | <5% | 5-30% | 30-60% | 60-90% | >90% |
|-----------------------|-----|-------|--------|--------|------|
| Stability             | Stable | Basic stable | Less stable | Worse stable | Unstable |

Table 2. Different failure probability of landslide stability (Zhang et al. 1994)
Fig. 5 shows that the primary control on slope stability is water level drawdown, because it is observed that the faster water level drawdown speed the higher failure probability. And according to the classification in Table 2, all the scenarios shown in Fig. 5 are worse stable, or absolutely unstable. This implies that poor drainage soil slopes are very likely to become unstable under the combined effect of rainfall and water level drawdown. Besides, the plots with same water level drawdown speed but different rainfall intensity show that the effect of rainfall is limited on slope stability here.

The reason for these observations lies in the drainage ability of soils. More specifically, most of the rainwater runs off rather than infiltrating into slope due to the limitation of drainage ability. Therefore, short-duration rainfalls hardly do great harm to the potential slip surfaces inside slope. However, when the reservoir water level decreases, the change of underground water table in soil slope always lags that in reservoir, causing great seepage forces on slope. It’s of great danger to the potential slip body, and the poorer drainage ability of soils the more greater seepage force acted on slip body.

4. Conclusions
A homogeneous soil slope has been modeled to evaluate the slope stability, under the combined effect of rainfall and water level drawdown. The analysis was carried out through conventional safety factor method and probabilistic approach. The observed results show that water level drawdown plays the dominant role in controlling slope stability of poor drainage soil slopes, while short-duration rainfall is a secondary influence. The reason for this is closely related to the drainage ability of soils. During water level drawdown period, the great seepage force caused by water level drawdown is the main reason to induce landslides, while poor drainage soil slopes are less sensitive to rainfall due to the limitation of drainage capacity.

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