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RELIABILITY ASSESSMENT OF SLOPE STABILITY UNDER DRAWDOWN OF RESERVOIR WATER LEVEL

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To investigate the influences of reservoir water level drawdown on slope stability, numerical simulation was carried out to examine the impacts of slope angle, soil permeability and water drawdown speed on pore water pressure change during seepage, as well as the slope stability number. It is found that reservoir water level drawdown, as the main contributing factor, possesses significant influence on slope stability. Slope stability decreases with reservoir water drawdown. In addition, there are interaction effect between slope angle, drawdown speed and soil permeability, with regard to the influences on slope stability. Based on the numerical results, polynomial regression models were developed to relate the slope stability number to key influencing parameters mentioned above. For comparison, the First-Order Reliability Method and Monte Carlo Simulation are adopted to calculate the slope failure probability P_f. Parametric studies with regard to the influences of these key variables on P_f are also carried out.

Keywords: reliability assessment, reservoir water level drawdown, two-phase flow, slope stability, FORM, Monte Carlo Simulation.

1 Introduction

The management of unfavorable geological slope has been one of the key scientific issues in the construction and operation of infrastructure in China. According to the previous research, more than 90% of the slope instability is associated with water, and the factor of water plays a major role in the process of slope instability (Wang and Li 2003). According to the studies of landslides occurred in the surrounding area of Roosevelt lake from 1941 to 1953, nearly 30% took place during the period of water level drawdowns (Nakamura 1990). Landslide disaster resulted from the water level fluctuation is one of the geological hazards existing in the reservoir areas. Particularly in the Three Gorges Reservoir (TGR), people's lives and properties are subjected to great potential threats. As is well known, the failure of Italian Vajont Dam slope in October 1963 caused by the fast reservoir impound resulted in the complete destruction of several villages downstream (Paronuzzi and Rigo 2013). After that the geologists fully realize the possible catastrophic consequences of reservoir slope failures, which pose great threats to the populated areas (Schuster 1979; Gutiérrez et al. 2015).

The approaches studying the water drawdown can be classified into two types. The first method focuses on the flow problem and do not consider any modification of the initial water pressure (Reinius 1954; Desai 1972, 1977; Pauls et al. 1999), and the influence of instantaneous water level change on pore water pressure is considered in the second method (Skempton 1954; Morgenstern 1963; Baker et al. 1993). For instance, the limit equilibrium method is used to analyse the influence of water level change in reservoir area by Morgenstern (1963), whose results show that the safety coefficient of slope increases with the reservoir water level. Then the question is further discussed with seepage force taken into account (Desai 1977; cousins 1978). In recent years, the numerical method has been widely used. Zheng et al. (2004) proposed a simplified calculation formula for the infiltration line of slope through expressions deduction. Later Zheng et al. (2007) deducted the analytical expression and numerical solution of wetting line by PLAXIS software. References about the influence of water level change on slope stability also include Lane and Griffiths. (2000), Berilgen. (2007), Liang et al. (2014). However, a systematic investigation of influences of the crucial parameters on slope stability is desirable.

This paper intends to describe the relationship between slope stability and influential factors based on the numerical results from Finite Difference code FLAC. The calculation results indicate that there is an interaction effect between slope stability and slope angle, drawdown speed, soil permeability, with regard to the influences on slope stability. In addition, reliability assessment was performed to examine the influences of these key parameters on the probability of unsatisfactory slope performance.

2 Numerical modelling and result analysis

Based on the flood control requirements, the TGR should be operated at a flood-control water level of 145 m during the flood period, starts to be impounded to the normal water level of 175 m in dry season (Su 2003). Figure 1 shows the numerical model. the permeability of soil and the curve of matrix suction can be adjusted automatically in the two-phase flow option in FLAC.

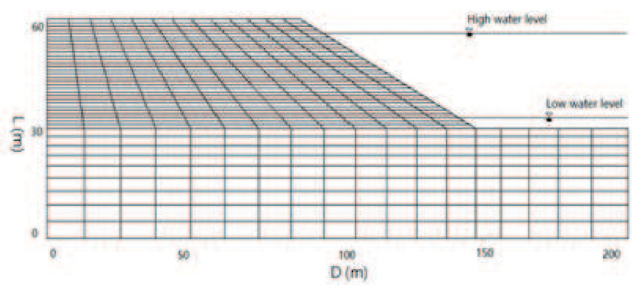

Fig.1 Physical model for the slope

In this paper, the drawdown speed is set to be 1m/d, 1.5m/d, 2m/d, slope angle is 15°, 20°, 30°, and soil permeability is 8.64 m/d, 0.864 m/d, 0.0864 m/d (Liu et al. 2005). In addition, based on the actual formation conditions of the TGR area, the basic geotechnical parameters are selected as: cohesion force c=24 kpa, frictional angle φ=23° (Ding et al. 2004)

The three factors include those with the drawdown speed υ, slope angle β and soil permeability k. Under normal test conditions, the number of three-factor tri-level test is 3^3, but the orthogonal test can be directly analysed by using only 9 groups. According to the engineering geological data and related literatures, the design level of factors is show as Table 1.

Table 1 Level of factors

Level	υ（m/d）	β（°）	k（m/d）
1	1	15	8.64
2	1.5	20	0.864
3	2	30	0.0864

Figure 2 shows the relation curves between stability coefficient Fs and height H during the water level drops. Some conclusions shown in following (1) the slope stability changes as the duration of reservoir water level decreases, and there's a minimum, it is in the position of H=20m, critical water table at 1/3 of slope depth, varies slightly with other factors; (2) the rate of reservoir water level drops has an important effect on the stability coefficient. For the same slope, with the increase of rate, the bank slope stability is decreased in the same condition of water level; (3) The initial value of safety factor is different, for example, the safety factor is 2.69 when the slope angle is 15°, and the safety factor is 1.64 when the slope angle is 30°. The reason is that the different slope angle determines the initial stress state of slope and controls the occurrence of potential landslide; (4) the stability of slope decreases with the decrease of permeability coefficient (slope instability when slope angle is 30°). At the same time, when the permeability coefficient is greater than the drawdown speed, the stability coefficient significantly increased.

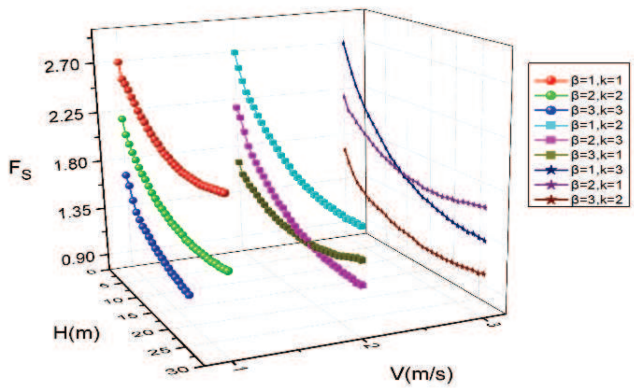

Fig.2 Stability comparison based on Orthogonal Test Scheme

3 Estimation model of stability number

Based on the results, a polynomial regression (PR) model has been developed for estimating the stability number Fs as a function of the four input parameters: slope angle β, magnitude of reservoir water level drawdown *H*, coefficient of permeability k, and drawdown speed υ. Table 2 lists the typical data sets for development of the estimation model.

Table 2 Typical data sets for development for the estimation model

β (°)	H (m)	k (m/d)	υ (m/d)	Fs	β (°)	H (m)	k (m/d)	υ (m/d)	Fs
15	4	8.64	2	2.440	20	5	8.64	1	1.943
15	25	8.64	2	2.055	30	10	0.864	1.5	1.192
15	10	0.864	2	2.150	30	15	0.0864	1.5	0.978
15	15	0.0864	2	1.871	30	20	0.864	1.5	1.053
15	10	0.864	1.5	2.065	20	15	8.64	1	1.675
20	25	0.0864	2	1.319	20	5	0.0864	1	1.729

Based on the least square method, the optimal regression equation for Fs takes the following form:

$$F_S = a_0 + a_1\beta + a_2H + a_3k + a_4\upsilon + a_5\beta^2 + a_6H^2 + a_7k^2 + a_8\upsilon^2 + a_9\beta H + a_{10}\beta k + a_{11}\beta\upsilon + a_{12}Hk + a_{13}H\upsilon + a_{14}k\upsilon \quad (1)$$

The values of the coefficients are shown in Table 3. Fig. 3 shows the plot of the stability number estimated by using Eq. (1) versus the FDM values for the 799 hypothetical cases. Eq. (1) is reasonably accurate with a high coefficient of determination (R^2) of 0.9697.

Table 3. Response surface coefficient for Fs

a_0	4.7977	a_4	-0.10287	a_8	0.11894	a_{12}	0.00135
a_1	-0.19278	a_5	0.003105	a_9	0.000953	a_{13}	0.001376
a_2	-0.08519	a_6	0.001316	a_{10}	-0.00017	a_{14}	-0.01333
a_3	0.16297	a_7	-0.01467	a_{11}	-0.00969		

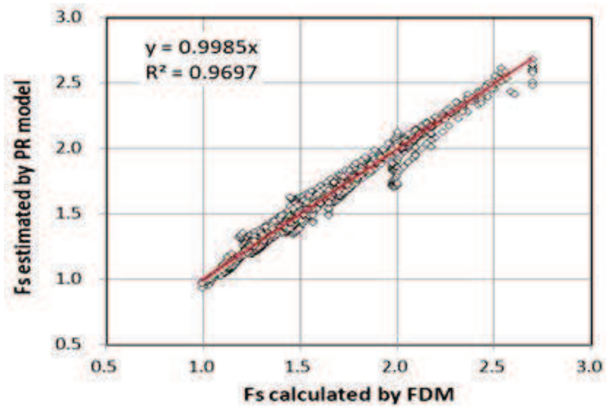

Fig.3 Predicted stability number Fs_{PR} versus the calculated Fs_{FDM}

4 Reliability assessment of slope stability

With determination of the performance function Eq. (1), reliability assessment of slope stability can be performed using First-order reliability method (FORM) (Low et al.2004; Zhang et al.2012), as shown in Fig. 4. The slope angle and the water level drawdown are treated as deterministic since the values of these two variables can be determined easily. The soil permeability k and the drawdown speed υ are regarded as random variables. The coefficient of variation (COV) for k is assumed to change from 0.1 to 0.6 considering that there is a great variation with regard to the permeability. While for υ, COV is 0.1 and 0.2, representing the good control of drawdown speed and the ordinary control, respectively. Failure occurs if the predicted stability number F_{SPR} is smaller than the unity.

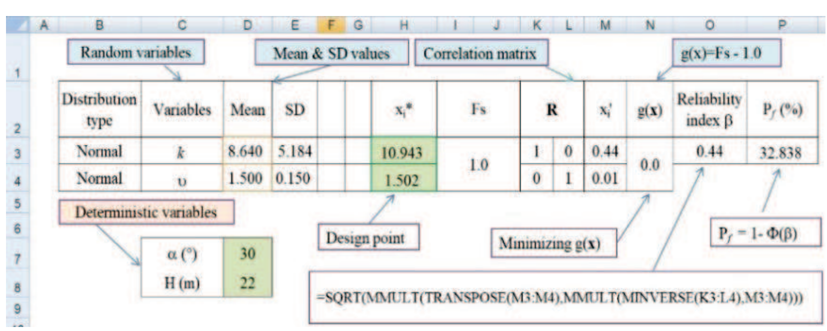

Fig. 4 Implementation of PR model into FORM Spreadsheet for reliability analyses

For illustrative purpose, Table 4 lists two cases used for reliability index. It should be noted that the only difference between the two cases lies in the value of soil permeability.

Table 4 Two cases for reliability analysis

Case No.	Parameter combination
1	α=30°, H=20 m, k=0.864 (average), υ=1.5 m/s (average)
2	α=30°, H=20 m, k=8.64 (average), υ=1.5 m/s (average)

Fig. 5a plots the reliability index β for the two cases, with assumption that COV_k ranging from 0.1 to 0.6 and COV_υ ranging from 0.1 to 0.2. It indicates that COV_υ has minimal impact on β and that the average soil permeability k significantly influences the β value. In addition, it is obvious that COV_k also greatly influences β since the reliability index decreases from 4.22 to 0.71 when the COV_k increases from 0.1 to 0.6. Accordingly, the probability of failure P_f plotted in Fig. 5b increased significantly from 0.1% to 23.9%. In this regard, for reliability assessment on influences of reservoir water drawdown on slope stability, both the average soil permeability and the variation values should be accurately measured and determined.

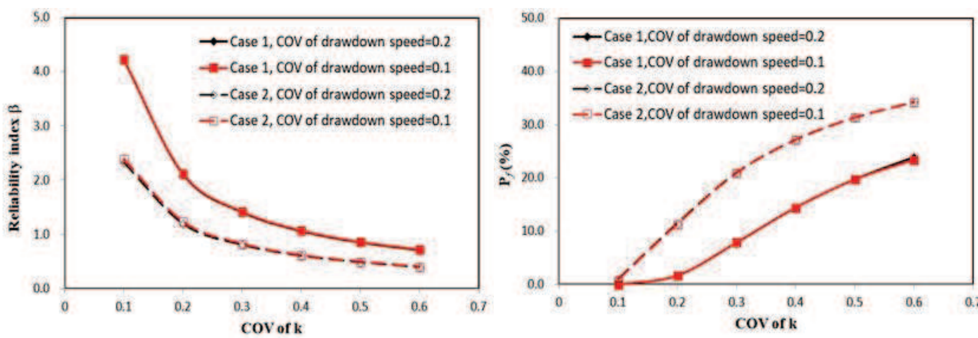

Fig. 5 Influence of COV of k and COV of υ on: (a) Reliability index β and (b) P_f

5 Summary and conclusions

A series of numerical simulations were carried out to examine the impacts of slope angle, soil permeability and water drawdown speed on slope stability. PR model relating the stability number to the influential factors was developed. Reliability assessment was performed to examine the influences of these key parameters on the probability of unsatisfactory slope performance. The main conclusions arrived at in this study include:

(1) Taking into account the effect of matrix suction, the F_S values calculated from the two-phase flow is greater than that from the single-stream flow (fully saturated).

(2) The slope stability is worsened when the reservoir water level is lowered. Fs decreased more if: a, the drawdown speed is greater; b, slopes are steeper, as well as, c, the slope is less permeable. In addition, there is a most critical water table, generally at height of 1/3 slope depth from the toe.

(3) An estimation model is developed for preliminary check of slope stability. Both the average soil permeability and the variation values influence the probability of slope failure. Thus these values should be accurately measured and determined.

It should be noted that both the shear strength parameters and the coefficient of permeability are assumed constants and uniform in this study. Actually, they vary with the volumetric water content changes induced by the water level variations. More complicated numerical analysis for real condition simulation will be performed in the future studies.

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