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ORIGINAL ARTICLE

Effect of hydraulic properties of soil and fluctuation velocity of reservoir water on landslide stability

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Abstract Water fluctuation is the main triggering factor of reservoir slope failures, especially in the area of the Three Gorges Reservoir of China. Fluctuation velocity of reservoir water and hydraulic properties of soil as defined by soil–water characteristic curve (SWCC), saturated permeability coefficient and unsaturated permeability function are key potential properties that control reservoir landslide stability. The effect of reservoir water fluctuation velocity and hydraulic properties of soil on landslide stability are investigated through a series of numerical simulations with different parameters. The results of simulations show that fitting parameters in the SWCC [i.e., *a*, *n*, *m* for Fredlund and Xing (Can Geo J, 31(3):521–532. doi:10.1139/t94-061, 1994) equations] have significant effect on the stability of landslide for reservoir water's drawdown or impounding process. The saturated permeability coefficient of soil and velocity of water level fluctuation have comprehensive (defined as Impact Factor, α) and significant influence on the stability of reservoir landslide. A relative equation: $m > \alpha > n > a$ has been drawn for the susceptibility of effect on the stability of reservoir landslide for the parameters "a", "n", "m" and "α".

Keywords Reservoir landslide · SWCC fitting parameters · Reservoir water fluctuation velocity · Factor of safety · Effect susceptibility

Introduction

Water fluctuation is one of the most recognized triggering factor of reservoir slope failure, especially in the area of the Three Gorges Reservoir of the Yangtze River, China, which experience 30 m of water fluctuation every year. After the water table of the Three Gorges Reservoir was first raised to 175 m (EL.) on Oct. 26, 2010, it is fluctuated periodically within the range of 145–175 m. The fluctuation has induced numerous landslides and large deformation of bank slopes. The Qianjiangping landslide occurred on 13 July 2003, and it was just 43 days after the initial impounding of the Three Gorges Reservoir to the water level of 135 m (Dai et al. 2004; Fourniadis and Liu 2007; Wang et al. 2008). Besides, the maximal accumulated monitoring deformation of Shuping landslide and Baishuihe landslide reached 1428 and 451 mm approximately in two water-fluctuated cycles. The locations of the three landslides are shown in Fig. 1.

A large number of experimental, numerical and monitoring studies have been conducted concerning the landslide stability with water fluctuation. The primary factor that leads to landslide from water fluctuation is the groundwater table or pore-water pressure in slope body. It

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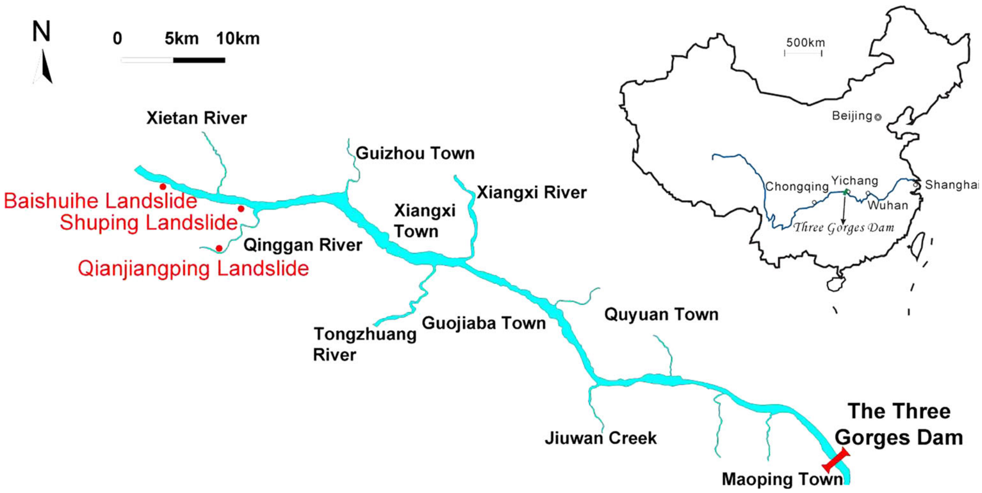


Fig. 1 Location of Qianjiangping Landslide, Shuping Landslide and Baishuihe Landslide

Fig. 2 Pictures of cores of Shuping Landslide

has been pointed out that there is a significant delay between groundwater level (Deng et al. 2005) or pore-water pressure (Jia et al. 2009) inside the slope and the filling or drawdown of the water level outside the slope, and such effect is controlled by speed of the water level fluctuation (Yan and Wang 2010), saturated permeability coefficient (Deng et al. 2005) and saturated state of the soil mass (Yan and Wang 2010). This phenomenon has led to different trends of variation for factor of safety (FoS) against water fluctuation (Lane and Griffiths 2000; Wang et al. 2007, 2014; Luo et al. 2010; Zangerl et al. 2010; Zhang et al. 2010, 2012; Cojean and Cai 2011; Pinyol et al. 2012; Paronuzzi et al. 2013; Wang and Xu 2013). The different tendencies are related not only to the landslide geological characteristics, but also the velocity of water level

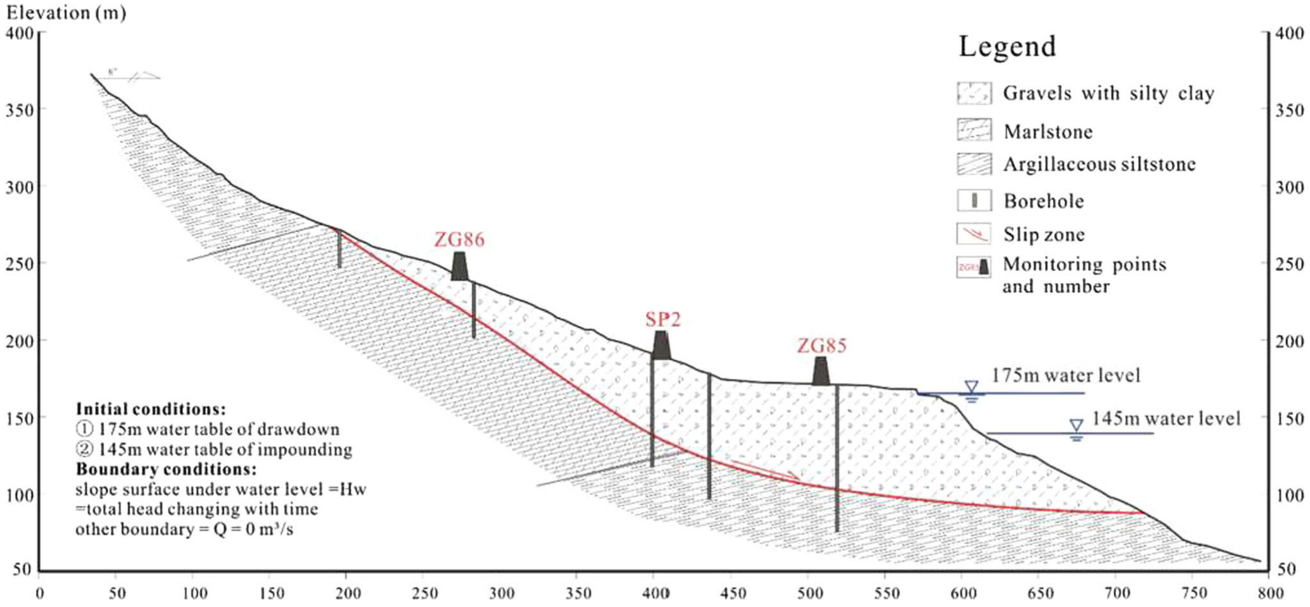


Fig. 3 Shuping landslide geological profile and studied hydraulic conditions (initial and boundary conditions)

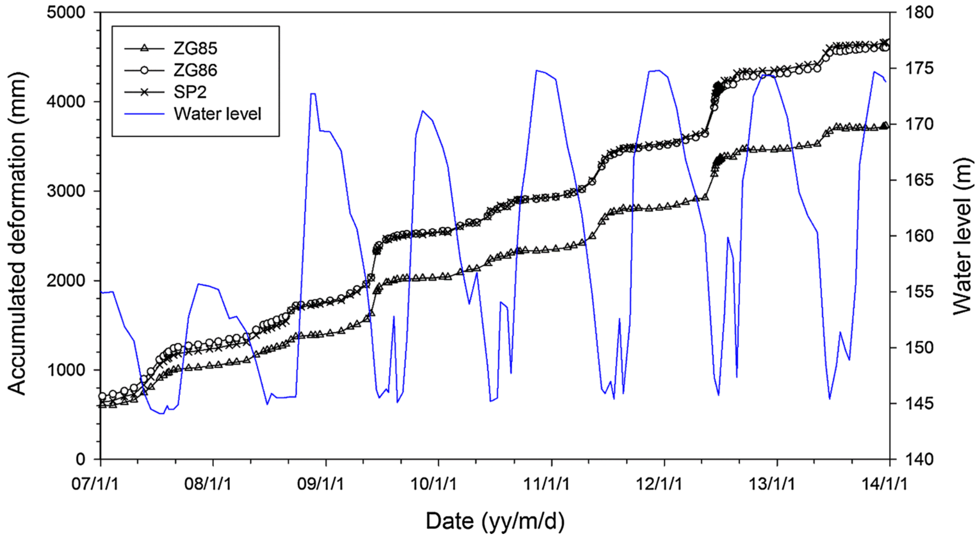


Fig. 4 Monitoring surface deformation by GPS of Shuping Landslide and reservoir water level fluctuation versus date

fluctuation and soil saturated permeability coefficient (Berilgen 2007; Song et al. 2011). However, there is a lack of knowledge about the comprehensive influence of water fluctuation velocity and hydraulic properties of soil (soil–water characteristic curve, saturated permeability and unsaturated permeability function) which play important roles in rainfall-induced slope failure (Rahimi et al. 2010). Therefore, the present study will focus on the effect of different hydraulic property and velocity of water level fluctuation on the stability of reservoir landslides.

Landslide model and properties

The example used in this study is Shuping Landslide, which is located on the right bank of the Yangtze River (Fig. 1). The Shuping Landslide is an ancient slide, which lies between elevation 65 and 400 m with a width of about 650 m. Boreholes indicating the landslide is between 25 and 74 m thick, and the landslide volume is about 20.7 million m^3. The slide body is composed of gravel with silty clay and the slip zone is silty clay with little gravel (Fig. 2). And the Landslide is underlain by muddy sandstone, sandy mudstone and marlstone of the Triassic Badong formation (T$_2$b). The geological profile is shown in Fig. 3.

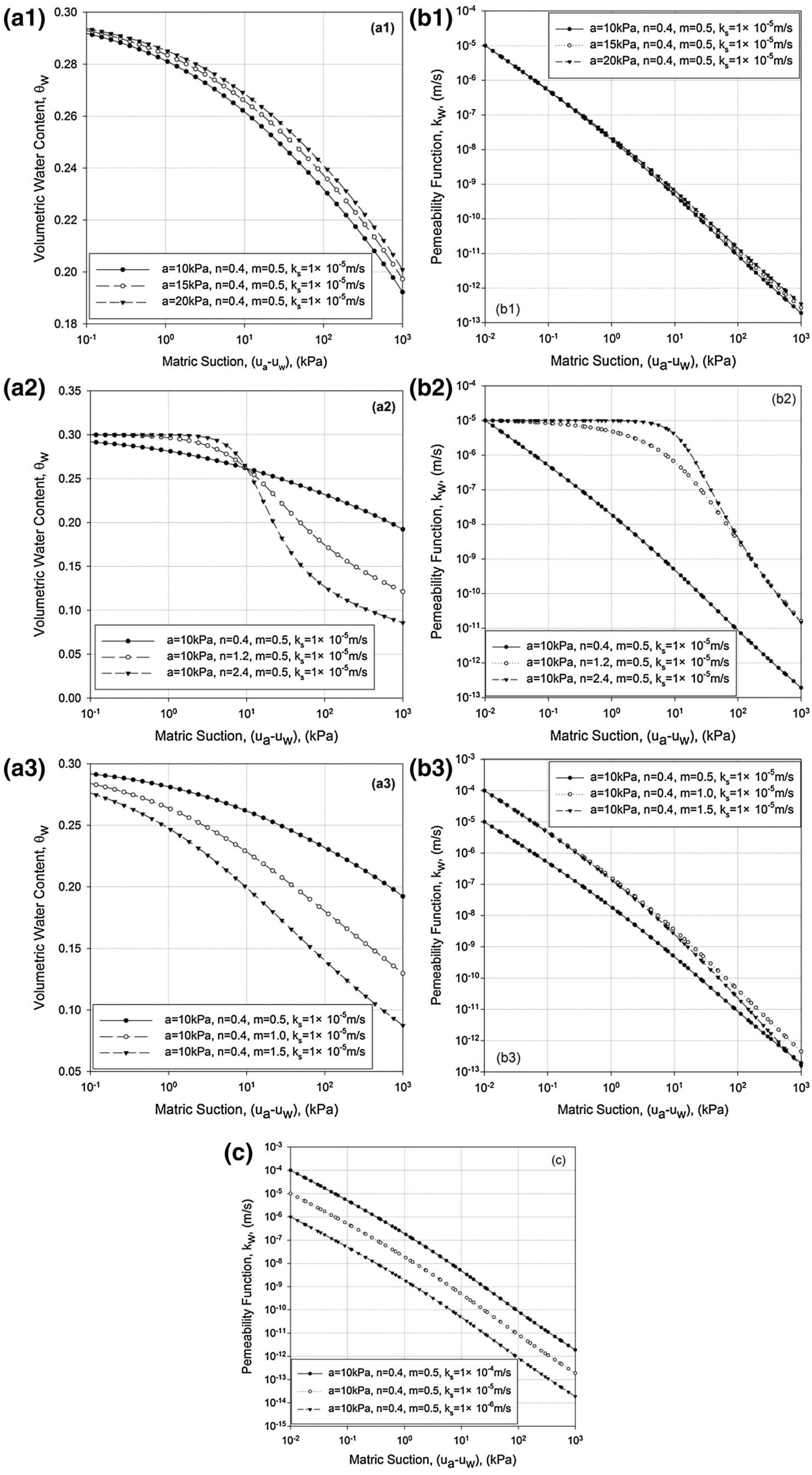
Figure 4 is the monitored surface deformation of Shuping landslide by GPS. The points ZG85, ZG86 and SP2 are shown in Fig. 3. As can be observed from Fig. 4, the reservoir water level fluctuation is the main factor for the deformation, especially during the drawdown stage. Meanwhile the deformation changes with different rates of reservoir water fluctuation (Fig. 4). For example, such rate is different in drawdown stage of the year 2010, 2011 and 2012, and the step of the monitoring curve is varied.

A simplified 2D numerical model with simplified geological stratum is established to represent the real Shuping Landslide conditions. The stratum of slide body is assumed as homogeneous material with equivalent parameters, and the spatial variability and anisotropy of the gravel with silty clay is ignored. A series of numerical tests are conducted by applying a time-dependent total head H_w on the slope surface under reservoir water level. The total head, H_w, fluctuates between 175 and 145 m with five uniform velocities, v, i.e., 0.1, 0.5, 1.0, 2.0 and 3.0 m/d, and those velocities are chosen to simplify the actual reservoir water fluctuation (water level fluctuated in Fig. 4) to avoid the nonuniform effect. The node flux Q with a value of zero was applied to other boundaries of the landslide, like the left, bottom, etc., to simulate no flow zone. The residual shear strength properties of the soil used was based on

Table 1 Parameters involved in the study

Study sets	a (kPa)	n	m	k_s (m/s)
A	$\begin{bmatrix}10\\15\\20\end{bmatrix}$	0.4	0.5	1×10^{-5}
B	10	$\begin{bmatrix}0.4\\1.2\\2.4\end{bmatrix}$	0.5	1×10^{-5}
C	10	0.4	$\begin{bmatrix}0.5\\1.0\\1.5\end{bmatrix}$	1×10^{-5}
D	10	0.4	0.5	$\begin{bmatrix}1 \times 10^{-6}\\1 \times 10^{-5}\\1 \times 10^{-4}\end{bmatrix}$

Fig. 5 SWCC and unsaturated permeability function, k_w, of soil: **a1** SWCC of different parameters "*a*"; **b1** k_w of different parameters "*a*"; **a2** SWCC of different parameters "*n*"; **b2** k_w of different parameters "*n*"; **a3** SWCC of different parameters "*m*"; **b3** k_w of different parameters "*m*"; **c** unsaturated permeability function of different k_s



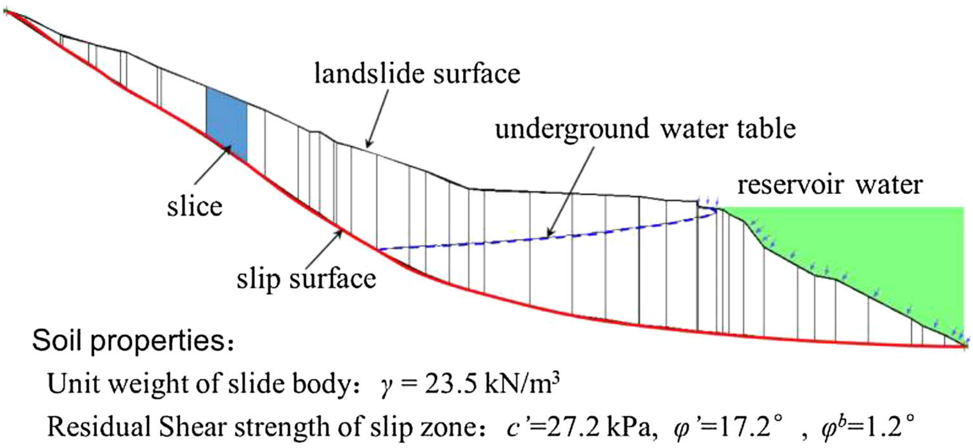


Fig. 6 Calculation model and soil properties for landslide stability analysis

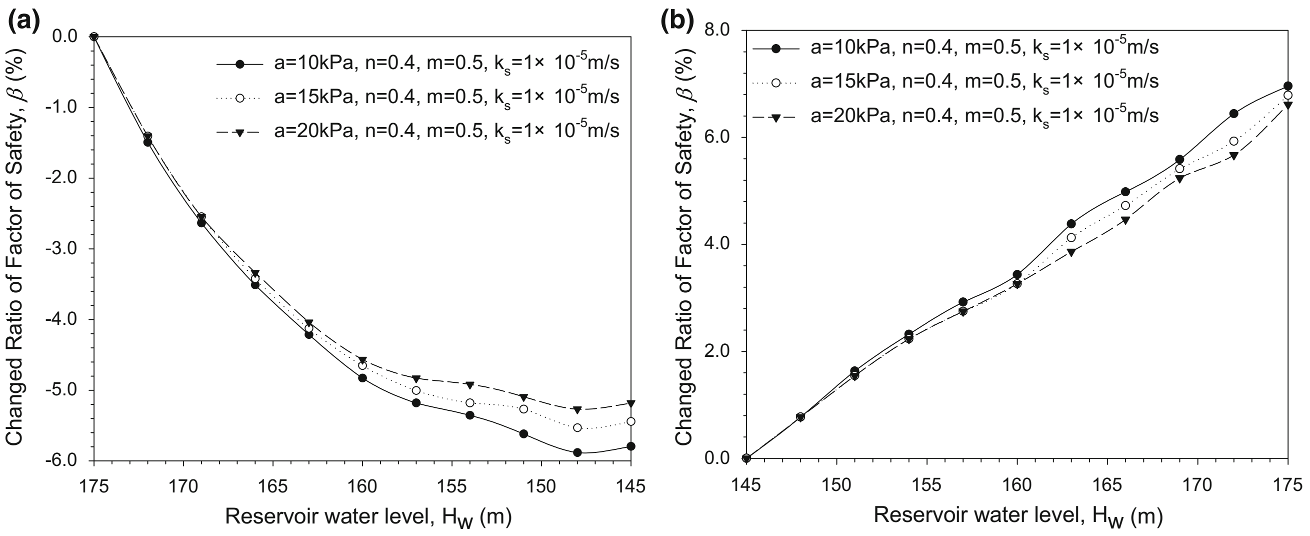


Fig. 7 Comparison of changed ratio of factor of safety, β, versus reservoir water level for different values of parameter "a": **a** drawdown with velocity, $v = 1.0$ m/d; **b** impounding with velocity, $v = 1.0$ m/d

laboratory test of soil from Shuping slip zone. A unit weight of soil, $\gamma = 23.5$ kN/m^3, effective cohesion, $c' = 27.2$ kPa, effective angle of friction, $\varphi' = 17.2°$, and rate of increase in shear strength caused by matric suction, $\varphi^b = 1.2°$, were used in the landslide stability analysis, and were kept constant for all cases.

Study of hydraulic properties of soil

The soil–water characteristic curve (SWCC), saturated permeability and unsaturated permeability function are referred to the hydraulic properties of soil. The equation proposed by Fredlund and Xing (1994) is used for the estimation of SWCC, and the unsaturated permeability function is predicted from the SWCC (Fredlund et al. 1994) in addition.

The SWCC is regulated by the fitting parameters "a", "n" and "m", and the equation is as follows (Fredlund and Xing 1994):

$$\Theta_w = C_\psi \frac{\Theta_s}{\left\{\ln\left[e + \left(\frac{\Psi}{a}\right)^n\right]\right\}^m} \tag{1}$$

where: Θ_w = the volumetric water content, C_ψ = a correction coefficient that allows a progressive decrease in water content at high suctions, forcing the function through a water content of zero at one million kPa suction. Θ_s = the saturated volumetric water content, e = the natural number (2.71828), Ψ = the negative pore-water pressure, and a, n, m = curve fitting parameters.

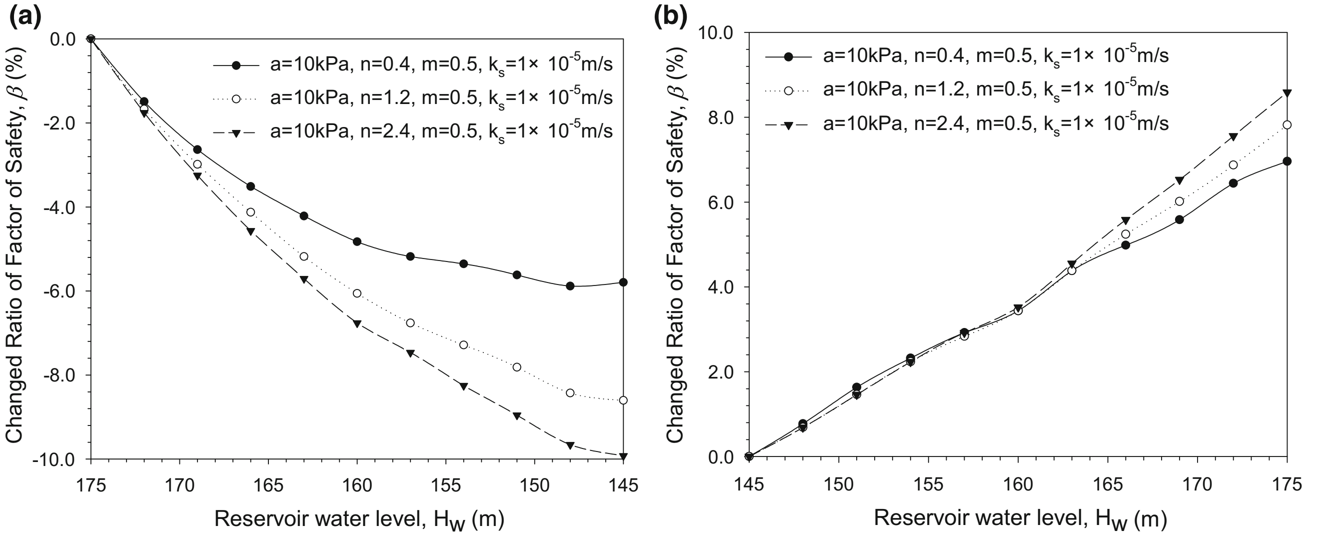


Fig. 8 Comparison of changed ratio of factor of safety, β, versus reservoir water level for different values of parameter "n": **a** drawdown with velocity, $v = 1.0$ m/d; **b** impounding with velocity, $v = 1.0$ m/d.

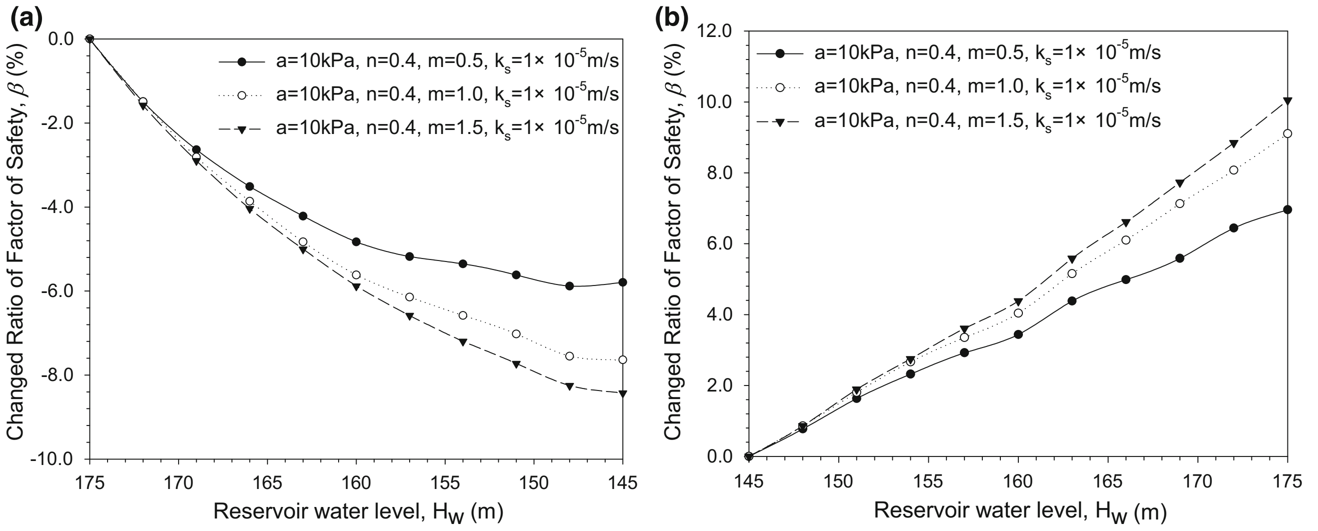


Fig. 9 Comparison of changed ratio of factor of safety, β, versus reservoir water level for different values of parameter "m": **a** drawdown with velocity, $v = 1.0$ m/d; **b** impounding with velocity, $v = 1.0$ m/d

Those fitting parameters and saturated coefficient of permeability, k_s, are the variable parameters in this study, as presented in Table 1.

Four sets of tests in Table 1 are performed to study the effect of hydraulic properties. And the parameters were determined according to Song et al. (2014). In each set, three parameters are fixed, while only one parameter is changed with three different values. In set A, parameter "a" is set to be 10, 15 and 20 kPa. In set B, parameter "n" is set to be 0.4, 1.2 and 2.4. In set C, parameter "m" is set to be 0.5, 1.0 and 1.5. In set D, parameter "k_s" is set to be 1×10^{-6}, 1×10^{-5} and 1×10^{-4} m/s. The SWCC and unsaturated permeability function, k_w, used are shown in Fig. 5.

Effect of parameters

Two analyses are performed to study the stability of landslide under different fluctuated velocity, seepage and stability analysis. The seepage analysis is performed by computing the pore-water pressures with the software SEEP/W (Geo-slope International Ltd. 2008a) under reservoir water fluctuation. Then the computed pore-water

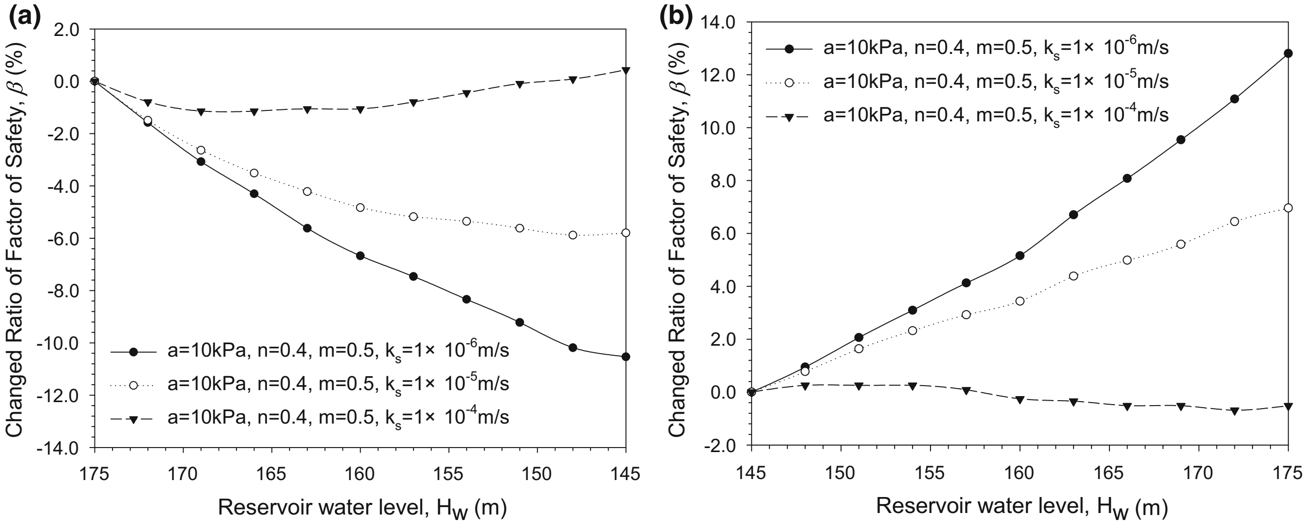


Fig. 10 Comparison of changed ratio of factor of safety, β, versus reservoir water level for different saturated coefficient of permeability, k_s: **a** drawdown with velocity, $v = 1.0$ m/d; **b** impounding with velocity, $v = 1.0$ m/d

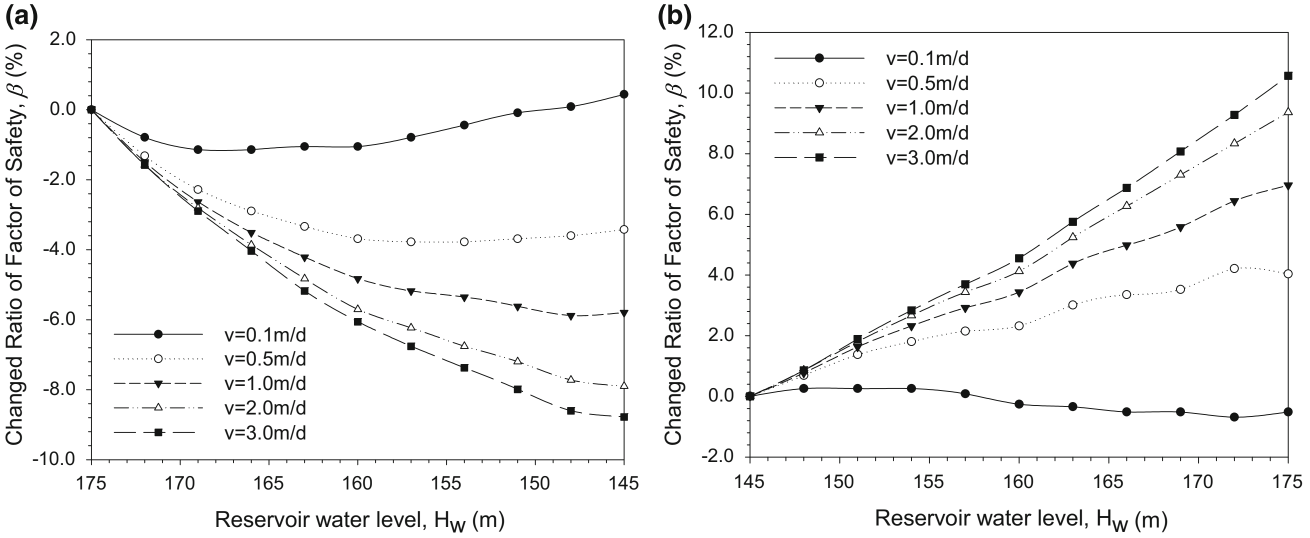


Fig. 11 Comparison of changed ratio of factor of safety, β, versus reservoir water level for different reservoir water-fluctuated velocities with $a = 10$ kPa, $n = 0.4$, $m = 0.5$, $k_s = 1 \times 10^{-5}$ m/s: **a** drawdown; **b** impounding

pressure is used to calculate the FoS by the Morgenstern-Price limit equilibrium method, which is a Half-sine function for slide function, through the software SLOPE/W (Geo-slope International Ltd. 2008b). And the slip surface is fully specified by the slip zone of Shuping Landslide, which is not changed in every analysis to avoid influence of slip surface location. The calculation model and slices for the stability analysis is shown in Fig. 6.

For comparing the results of stability, changed ratio of factor of safety (CRFS), β is proposed in the study. It is defined as follows:

$$\beta = \frac{F_{si} - F_{s0}}{F_{s0}} \times 100\,\% \qquad (2)$$

where F_{si} = FoS at each time step; F_{s0} = initial value of FoS, which was the FoS when water level is 175 m in reservoir water drawdown and 145 m for impounding.

Effect of parameter “*a*”

Figure 7a, b show the variation of CRFS, β, versus reservoir water level for the landslides with different values of

Table 2 Changed ratio of factor of safety with different impact factors

Reservoir water level (m)	Changed ratio of factor of safety, β (%)			
	$\alpha = 0.12$		$\alpha = 1.16$	
	$v = 0.1$ m/d $k_s = 1 \times 10^{-5}$ m/s	$v = 1.0$ m/d $k_s = 1 \times 10^{-4}$ m/s	$v = 0.1$ m/d $k_s = 1 \times 10^{-6}$ m/s	$v = 1.0$ m/d $k_s = 1 \times 10^{-5}$ m/s
175	0.00	0.00	0.00	0.00
172	−0.79	−0.79	−1.49	−1.49
169	−1.14	−1.14	−2.63	−2.63
166	−1.14	−1.14	−3.51	−3.51
163	−1.05	−1.05	−4.21	−4.21
160	−1.05	−1.05	−4.83	−4.83
157	−0.79	−0.79	−5.18	−5.18
154	−0.44	−0.44	−5.36	−5.36
151	−0.09	−0.09	−5.62	−5.62
148	0.09	0.09	−5.88	−5.88
145	0.44	0.44	−5.79	−5.79
145	0.00	0.00	0.00	0.00
148	0.26	0.26	0.77	0.77
151	0.26	0.26	1.63	1.63
154	0.26	0.26	2.32	2.32
157	0.09	0.09	2.92	2.92
160	−0.26	−0.26	3.44	3.44
163	−0.34	−0.34	4.38	4.38
166	−0.52	−0.52	4.98	4.98
169	−0.52	−0.52	5.58	5.58
172	−0.69	−0.69	6.44	6.44
175	−0.52	−0.52	6.96	6.96

parameter “*a*”. The velocity of reservoir water fluctuation is $v = 1.0$ m/d in both drawdown and impounding condition. As shown in Fig. 7, the change of parameter “*a*” had little effect on the CRFS, β, for both drawdown and impounding processes, especially for the impounding condition. The rate of decrease in the CRFS, β, versus water level is faster for the soil with smaller parameter “*a*” when the reservoir water level is declining. Meanwhile, β increased quickly for the soil with smaller parameter “*a*” when the reservoir water level is rising. Basically, the greater the parameter “*a*”, the smaller is the absolute value of β, while there is almost no effect of parameter “*a*” on β in early period of water level change, and the influence is more obvious during the drawdown or impounding process of reservoir water.

In the soil–water characteristic curve (SWCC), a higher value of parameter “*a*” means a higher volumetric water content, θ_w, and permeability function, k_w (Fig. 5a1, b1) and the movement of water is faster in unsaturated soil. Therefore, the absolute value of CRFS, β, is smaller for a soil with a higher value of parameter “*a*”. Those findings are consistent with the results of Rahimi (Rahimi et al. 2010) on rainfall-induced landslide.

Effect of parameter “*n*”

Figure 8a, b shows the variation of CRFS, β, versus reservoir water level for the landslides with different values of parameter “*n*”. The velocity of reservoir water fluctuation was $v = 1.0$ m/d in drawdown and impounding condition. As shown in Fig. 8, the rate of decrease in the CRFS, β, versus water level is faster for the soil with higher parameter “*n*” when the reservoir water level is declining. And the β increases quickly for the soil with higher parameter “*n*” when the reservoir water level is rising. The influence of parameter “*n*” on β is similar to that of parameter “*a*”, which has a more significant effect during the drawdown or impounding process of reservoir water, although such effect is negligible in early period.

Effect of parameter "*m*"

Figure 9a, b shows the variation of CRFS, β, versus reservoir water level for the landslides with different values of parameter "*m*". The velocity of reservoir water fluctuation is $v = 1.0$ m/d in drawdown and impounding condition. As shown in Fig. 9, the decrease rate of the CRFS, β, versus water level is faster for the soil with higher parameter "*m*" when the reservoir water level is declining. The β increases quickly for the soil with higher parameter "*m*" when the reservoir water level is rising. Those trends are similar to the effect of parameter "*n*". For the drawdown or impounding process, the variation of parameter "*m*" has a significant effect on CRFS, β.

Effect of saturated permeability coefficient, k_s

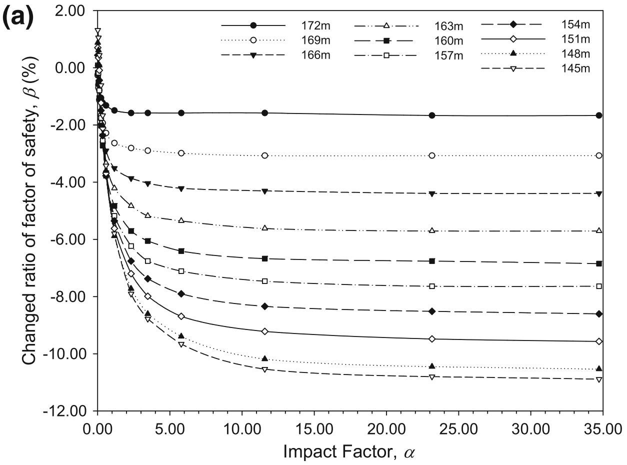
Figure 10a, b shows the variation of CRFS, β, versus reservoir water level for the landslides with different saturated permeability coefficient, k_s. The fluctuated velocity, v is constant with a value of 1.0 m/d for both drawdown and impounding. As shown in Fig. 10a, b, the curve amplitude of CRFS, β, was small when the saturated permeability coefficient k_s is 1×10^{-4} m/s, which means the β did not change significantly with the reservoir water level rise or decline. However, the β changed obviously versus the variation of reservoir water level for the saturated permeability coefficient $k_s = 1\times10^{-5}$ m/s and $k_s = 1\times10^{-6}$ m/s. The smaller k_s is, the faster β changes. In other words, variation of the saturated permeability coefficient, k_s, has a significant effect on the CRFS, β.

Effect of velocity of water level fluctuation, v

The variation of CRFS, β, versus reservoir water level for the landslides with different fluctuated velocity, v, is shown in Fig. 11a, b. The parameters of soil–water characteristic curve and saturated permeability coefficient are $a = 10$ k Pa, $n = 0.4$, $m = 0.5$, $k_s = 1\times10^{-5}$ m/s. In the case of $v = 0.1$ m/d, the CRFS, β, decreases at first and then increases with a declining water level and the extreme value is -1.14 % at 166 and 169 m water level (Fig. 11a). Figure 11b shows that the β increases in the beginning and decreases later with a rising water level and the maximum is 0.26 % at 148–154 m water level in the case of $v = 0.1$ m/d. However, the β changes more obviously against the variation of reservoir water level when the velocity of water level fluctuation is 0.5–3.0 m/d. And the β changes faster with a higher velocity. In other words, variation of the velocity of water level fluctuation, v, has a significant effect on the CRFS, β.

Comprehensive influence of k_s and v

Although the saturated permeability coefficient, k_s, and velocity of water level fluctuation, v, have significant influence on the stability of the landslide, both of them may be a comprehensive influence. An evaluating index, impact factor (IF), α, is therefore proposed to comprehensively estimate their coupled influence on the landslide stability, and α is defined as:



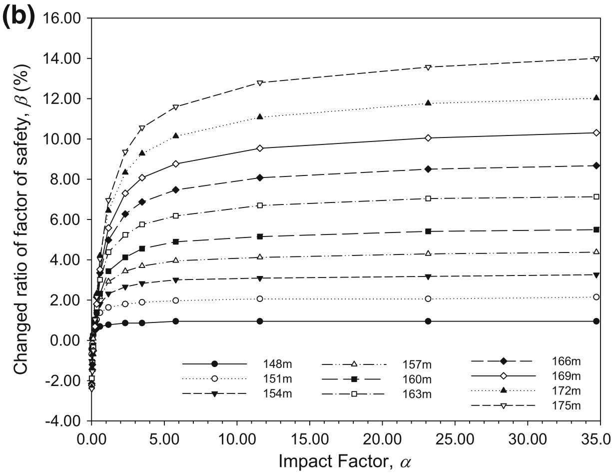
172m: $\beta=0.12\times\log_{0.5}(1190.7\times\alpha)$ $R^2=0.883$ 169m: $\beta=0.27\times\log_{0.5}(278.12\times\alpha)$ $R^2=0.911$

166m: $\beta=0.42\times\log_{0.5}(117.87\times\alpha)$ $R^2=0.928$ 163m: $\beta=0.58\times\log_{0.5}(66.32\times\alpha)$ $R^2=0.939$

160m: $\beta=0.71\times\log_{0.5}(53.36\times\alpha)$ $R^2=0.940$ 157m: $\beta=0.84\times\log_{0.5}(35.55\times\alpha)$ $R^2=0.937$

154m: $\beta=0.98\times\log_{0.5}(25.24\times\alpha)$ $R^2=0.939$ 151m: $\beta=1.13\times\log_{0.5}(19.57\times\alpha)$ $R^2=0.938$

148m: $\beta=1.26\times\log_{0.5}(16.85\times\alpha)$ $R^2=0.937$ 145m: $\beta=1.35\times\log_{0.5}(13.56\times\alpha)$ $R^2=0.936$



148m: $\beta=0.16\times\ln(44.32\times\alpha)$ $R^2=0.852$ 151m: $\beta=0.37\times\ln(27.74\times\alpha)$ $R^2=0.912$

154m: $\beta=0.58\times\ln(20.5\times\alpha)$ $R^2=0.940$ 157m: $\beta=0.81\times\ln(15.8\times\alpha)$ $R^2=0.950$

160m: $\beta=1.06\times\ln(11.54\times\alpha)$ $R^2=0.958$ 163m: $\beta=1.32\times\ln(12.87\times\alpha)$ $R^2=0.959$

166m: $\beta=1.59\times\ln(12.59\times\alpha)$ $R^2=0.962$ 169m: $\beta=1.88\times\ln(11.7\times\alpha)$ $R^2=0.958$

172m: $\beta=2.16\times\ln(12.5\times\alpha)$ $R^2=0.960$ 175m: $\beta=2.47\times\ln(12.06\times\alpha)$ $R^2=0.958$

Fig. 12 Comparison of changed ratio of factor of safety, β, versus impact factor, α, for different reservoir water level with $a = 10$ kPa, $n = 0.4$, $m = 0.5$: **a** drawdown; **b** impounding

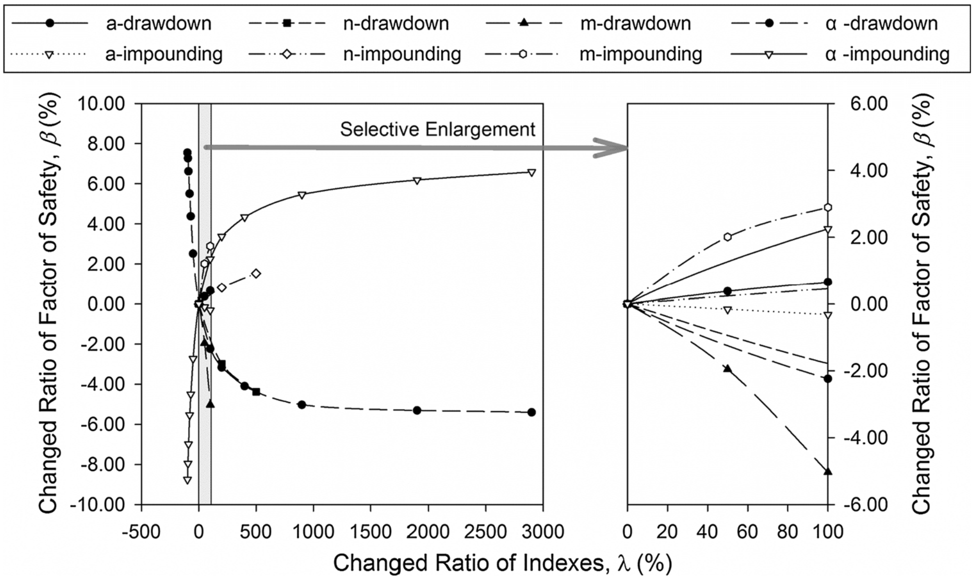


Fig. 13 Changed ratio of factor of safety, β, versus changed ratio of indexes, λ, for different parameters "a", "n", "m" and "α" with reservoir water level of 145 m for drawdown and 175 m for impounding

$$\alpha = \frac{v}{k_s} \tag{3}$$

where the k_s is the velocity of water flowed in the soil and the v was the velocity of the reservoir water level fluctuation. On the other hand, the CRFS of landslide, β, is unchanged if the α is the same with different v and k_s. Table 2 shows the four cases of variation of CRFS against different impact factors in the study. Therefore, the α can reflect the comprehensive influence of k_s and v on landslide safety.

Figure 12 shows CRFS, β, versus IF, α, for different reservoir water level. Figure 12a indicates that CRFS is approximately logarithmic decrement with increase of IF in different water levels for reservoir drawdown. And the fitted equations are shown in Fig. 12a.

The CRFS is approximately logarithmic increment with increase of IF in different water level under reservoir impounding as shown in Fig. 12b. And the curves of β are similar to the ones with rising reservoir water level, and the associated fitted equations are presented in Fig. 12b.

Susceptibility to the influence of hydraulic properties and fluctuation velocity

Taking changed ratio of indexes, λ, defined in the following equation, as x-axis and CRFS, β, as y-axis, the relationship is plotted in Fig. 13.

$$\lambda = \frac{X_i - X_0}{X_0} \times 100\,\% \tag{4}$$

where X_i = value of "a", "n", "m" or "α"; X_0 = initial value of "a" (10 kPa), "n" (0.4), "m" (0.5) or "α" (1.16).

The value of β is also calculated by Eq. (2). But, F_{si} = FoS for different parameters of "a", "n", "m" or "α" with end water level of 145 m for reservoir water drawdown and 175 m for impounding; F_{s0} = FoS with $a = 10$ kPa, $n = 0.4$, $m = 0.5$, $\alpha = 1.16$ at the end level of reservoir water drawdown or impounding.

Figure 13 shows that the variation in the CRFS, β, is fast to slow with the increase of the changed ratio of indexes, λ, especially for the curve of "α-drawdown" and "α-impounding". The CRFS, β, approximates to be a logarithmic decrement with increase of changed ratio of α under reservoir drawdown. However, the convex curve for impounding indicates that there is a logarithmic increment with increase of changed ratio of α. In the range of -100 to 0 for λ, the β increases for impounding or decreases for drawdown rapidly, while the change is smaller in the range of 0–1000.

The part in range of 0–100 is selectively enlarged to exhibit the different influence of "a", "n", "m" and "α" on the landslide stability. The enlargement shows that the susceptibility of the landslide stability to the 4 parameters "a", "n", "m" and "α" satisfies the following relative relationship:

$$m > \alpha > n > a \tag{5}$$

Conclusions

Fitting parameters [i.e., a, n, m for Fredlund and Xing (1994) equations] in the soil–water characteristic curve (SWCC) have significant effect on the stability of landslide during the drawdown or impounding process of reservoir water. The effect of parameters “a”, “n” and “m” on the Changed Ratio of FoS (CRFS) of landslide gradually increases with the order of “a”, “n”, “m”. The soil with a lower value of parameter “a”, “n” and “m” would experience a smaller absolute value of CRFS. In the presented example of reservoir landslide stability analysis, the statistical parameter “m” is the most important to FoS in all three hydraulic properties of soil. So it should be exactly for reservoir slope stability analysis.

The saturated permeability coefficient of soil and velocity of water level fluctuation are comprehensive and significant influence on the stability of reservoir landslide. The CRFS of landslide shows an approximately logarithmic decrement for reservoir drawdown or logarithmic increment for impounding with increase of IF, α (comprehensive influence indicator).

The susceptibility of the reservoir landslide stability to the parameters “a”, “n”, “m” and “α” satisfies the relative relationship: $m > \alpha > n > a$.

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