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ORIGINAL PAPER

Transient stability analysis method and sensitivity study of unsaturated soil slopes under consideration of rainfall conditions

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Abstract
The infiltration of rainfall is the key external factor that induces landslides, while the infiltration-induced soil strength decay and volume change are important internal factors for landslides. How to consider the impact of transient changes in unsaturated soil strength and volume on the safety factor during rainfall is a key problem to be solved in the prediction of landslides on unsaturated soil slopes. In this paper, transient stability analysis of unsaturated soil slopes is carried out based on GEO finite element software, and sensitivity analysis of factors affecting the slopes is carried out based on grey-scale correlation analysis. The results of the study show that transient stability analysis of unsaturated soil slopes by GEO is fully feasible. Slope instability is typically characterised by shallow instability damage when considering the strength decay of unsaturated soils due to rainfall infiltration. Sensitivity analysis based on grey-scale correlation shows that the factors affecting the stability coefficient in order of sensitivity are internal friction angle φ > cohesion C' > infiltration coefficient K > rainfall ephemeris H > heaviness γ > rainfall intensity P.

Keywords Unsaturated soils · Rainfall infiltration · Finite element · Grey-scale association · Slope stability

Introduction

The influence of rainfall infiltration on the stability of slopes is extremely important (Wu et al. 1999; Xu et al. 2006; Yao et al. 2002), and the prediction of rainfall-induced slope instability is a difficult problem to be solved in practical engineering. Most landslide engineering studies show that landslides usually occur after rainfall, but the internal causes are due to the fact that the shallow soils of the slopes are mostly unsaturated soils that will gradually become saturated under the infiltration of rainfall, while the change in saturation will cause a sharp decrease in the matrix suction of the soil. According to the unsaturated soil calculation theory proposed by Fredlund et al. (1978) and Fredlund and Rahardjo (1993), the decay of the matrix suction will lead to a significant decrease in the shear strength of the soil. When the rainfall intensity and duration exceed a limit, the infiltration of rainwater will reach a certain depth, which in turn will cause changes in the instability of the slope.

The key problem in predicting slope instability under rainfall conditions is how to integrate the effects of rainfall infiltration and the decay of soil strength with changes in soil water content on the transient stability of slopes. In his research, Chen (1997) and Chen and Chen (2001) have given a solution to this problem by proposing a numerical solution to the rainfall infiltration process while improving the simplified Janbu model (Lu et al. 2018). Numerical calculations were also given by the JA2 program to verify the feasibility of the method. However, the development of numerical simulation programs is limited by the fact that the method is not widely used. A major update of the general purpose FEA software GEO-Studio was made in 2017, in which the SEEP-SIGAM-SLOP module is used to perform unidirectional fluid-structure coupling calculations and thus transient stability analyses considering changes in the strength of unsaturated soils under rainfall infiltration conditions. However, the use of GEO for slope transient stability analysis under rainfall conditions has

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rarely been reported, and quantitative sensitivity analysis of the effect of different parameter changes on slope transient stability under rainfall conditions is even less common.

In this study, the transient stability simulation method for unsaturated soil slopes considering rainfall is proposed based on the flow-structure coupling calculation of GEO software, using the example given in the literature (Chen and Chen 2001) as an example. The discrepancies between the results of the literature (Chen and Chen 2001) and the GEO calculations are explored. A sensitivity analysis of the effect of the theory on the change of different parameters on slope stability under rainfall conditions is also carried out by means of grey-scale correlation theory. The research results of this paper can provide some reference for the study of transient stability analysis methods and the influence of law of parameters of unsaturated soil slopes under rainfall conditions (Jia and Zhou 2020).

Theory for calculating transient stability of unsaturated slopes

The study of rainfall infiltration-induced soil strength decay and consequently slope instability must firstly identify the changes in the seepage field formed by the rainfall infiltration process (Thanabalan 2018). Secondly, it is necessary to consider the change in soil strength due to the change in pore water pressure caused by the change in seepage field. In turn, the change in stability due to the change in soil capacity and soil strength caused by the infiltration of rainfall must be considered.

Saturated-unsaturated seepage theory

A number of engineering examples show that the infiltration of rainfall into the shallow soil of slopes is a classic saturated-unsaturated seepage process. The seepage control equation is mostly based on the saturated-unsaturated seepage equation proposed by Richards (1931):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t} \tag{1}$$

in which h is the matrix suction head and k is the unsaturated permeability coefficient.

In the GEO software SEEP/W is calculated for seepage under constant total stress conditions. It is also assumed that the soil pore pressure remains constant during transient calculations, so that its actual seepage control equation is as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+Q=m_w\gamma_w\frac{\partial h}{\partial t} \tag{2}$$

in which h is the matrix suction head, k is the unsaturated permeability coefficient, m_w is the slope of the water storage rate, γ_w is the water volume weight and Q is the boundary flow rate.

Theory of shear strength of unsaturated soils

The theory for calculating the shear strength of unsaturated soils uses the bivariate formulation proposed by Fredlund et al. (1978) and Fredlund and Rahardjo (1993):

$$\tau_f=c'+(\sigma_n-\mu_a)\tan\varphi'+(\mu_a-\mu_w)\tan\varphi^b \tag{3}$$

in which c' is the effective cohesion, φ' is the effective angle of internal friction, μ_a is the pore air pressure, μ_w is the pore water pressure and φ^b is the angle of internal friction that varies with the suction of the substrate.

Chen and Chen's (2001) study uses a fitted strength curve with water content as a variable for unsaturated soil shear strength calculations, which is calculated as follows:

$$c=\begin{cases}\dfrac{1.089-S_r}{0.096S_r+0.0075} & (0\le S_r\le 0.9)\\ 2.01 & (0.9\le S_r\le 1)\end{cases} \tag{4}$$

in which S_r is the water content of the soil.

Theory for calculating transient stability of unsaturated slopes

The formula for calculating the slip stability factor of unsaturated slopes considering rainfall infiltration is as follows:

$$F_s=\frac{\sum\limits_{i=1}^{ns}\dfrac{c_i'bi+(W_i+p_i\cos\beta_i-\mu_a b_i)\tan\varphi_i'+(\mu_a-\mu_w)\tan\varphi^b}{[1+(\tan\varphi_i'\tan\alpha_i)/F_s]\cos\alpha_i}}{\sum\limits_{i=1}^{ns}w_i\sin\alpha_i-r_ip_i} \tag{5}$$

in which i is soil bar number, c_i' effective cohesion, W_i mass, P_i water pressure, β_i dip angle, μ_a pore pressure, b_i width of soil bar, $\varphi_{i'}$ angle of internal friction, μ_w pore water pressure and φ^b friction angle controlled by matrix suction.

The formula used in Chen and Chen's (2001) study for calculating the slip stability factor of unsaturated slopes is an improvement on the simplified Janbu method and is calculated as follows:

$$F_s=\frac{\sum(c_ib_i+W_i\tan\phi_i)\sec^2\theta_i/[1+\tan\theta_i/F_S]}{\sum W_i\tan\theta_i} \tag{6}$$

in which W_i is the mass, b_i the width of the soil strip, c_i the effective cohesion, ϕ_i the angle of internal friction and θ_i the horizontal inclination of the sliding surface.

Equations (5) and (6) are the equations for calculating the factor of safety for the stability of unsaturated soil slopes, both of which need to be solved by iteration.

Finite element modelling

Computational models

The finite element model in this paper is based on Chen and Chen's (2001) study. The slope section is shown in Fig. 1a. The soil slope is divided into two layers $A^{'}B^{'}C^{'}D^{'}$ is the first layer which is affected by rainfall, $B^{'}C^{'}E^{'}F^{'}G^{'}$ is the second layer, and it is assumed that this layer is not affected by rainfall. Chen and Chen (2001) does not give specific data for the second layer of soil, so this paper makes assumptions according to Fig. 1. As the effect of rainfall on this layer is not considered, its specific dimensions do not affect the results of the analysis. Three measurement points were set up at the top, middle and foot of the soil slope in the depth direction to observe the changes of various parameters during the rainfall infiltration process, and the model grid was divided as shown in Fig. 1b.

Boundary conditions

The left and right sides and the bottom of the model are set as impermeable boundaries. The upper part is set as a flow boundary, and the effect of the initial water level is not considered. The rainfall flow boundary is set to 15 mm/h (Chen and Chen 2001), and the initial percolation condition of the model is based on the volumetric water content of 0.08 given in Chen and Chen's (2001) study. The initial water content cannot be specified directly in the SEEP/W module and is set indirectly through the pore pressure, which is set to −500 kPa according to the conversion.

Calculation parameters

The physical and mechanical parameters of the slope soils were determined according to Chen and Chen's (2001) study, and the specific values of each parameter are shown in Table 1. The soil and water characteristic curves and infiltration function curves were estimated according to the built-in VG model of GEO, and the specific function curves are shown in Fig. 2. It is important to point out that GEO's consideration of the strength of unsaturated soils during transient analysis is

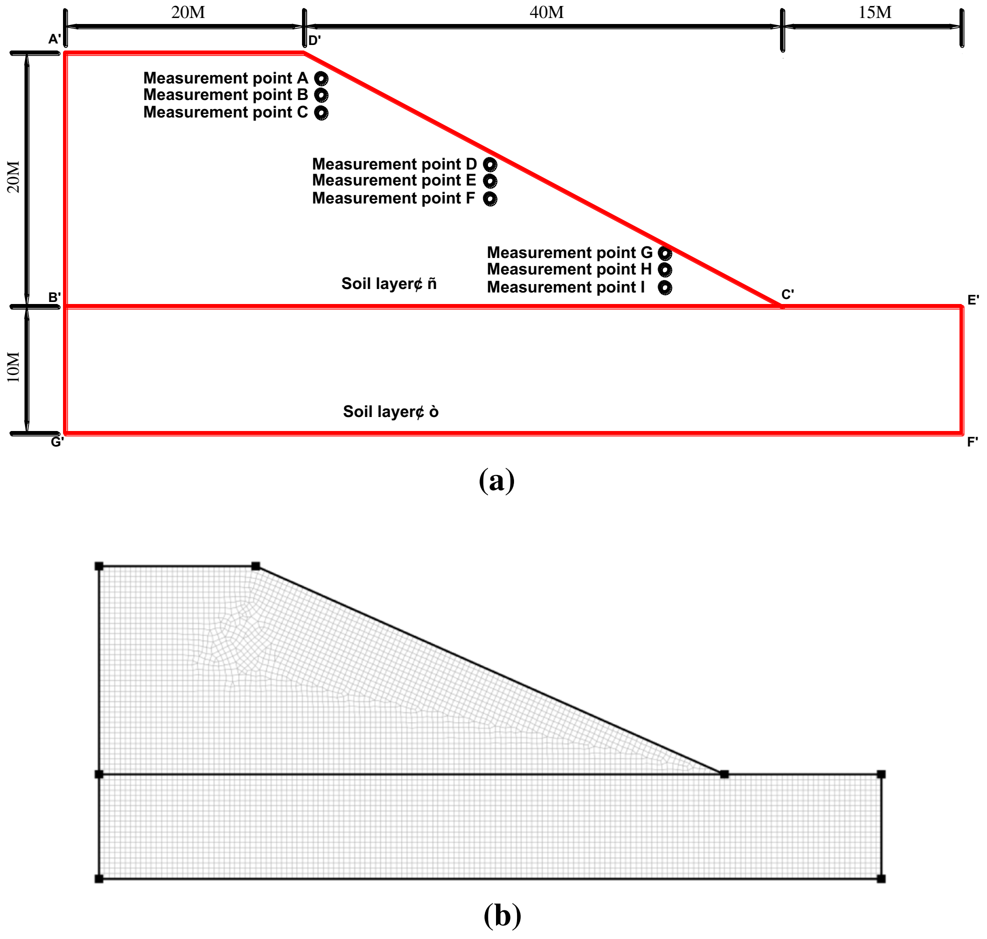


Fig. 1 Calculated model cross-section and meshing. **a** Diagram of the slope section. **b** Model grid

Table 1 Physical and mechanical parameters of materials

Materials	k_{sat}/(m.h^{-1})	γ_{sat}/(kN.h^{-3})	c'/(kPa)	φ'/(°)	φ^b/(°)
Soil layer I	0.047	16.2	2.01	4.02	Determined from moisture content curve
Soil layer II	0.047	20	100	25	None

based on the variation of φ^b. In general, this parameter is taken to be 0 by default; in other words, the change in soil strength due to the change in this parameter is not taken into account. Therefore, the initial φ^b value must be set in the transient strength analysis. And in this paper, the φ^b value is determined from the water content curve at a residual water saturation of 10% of the saturated water content. The infiltration function and the water-soil characteristic curve are shown in Fig. 2. It is also important to clarify that for the analysis of the transient stability of unsaturated soils caused by rainfall infiltration, the change in capacity due to rainfall infiltration must also be taken into account. Therefore, the change in material capacity with respect to the water content curve needs to be specified in the material definition in order to be considered.

Analysis settings

In this paper, three modules, SEEP-SIGMA-SLOP, are used for coupling calculations. The transient seepage field of the rainfall process is obtained by SEEP. The SEEP calculation results are coupled into the SIGMA module to obtain the transient stress and strain fields during the infiltration process. Finally, these two results are coupled into the SLOP module for transient stability analysis. The above process is achieved by step-by-step iterative calculations. In order to simulate the transient changes as much as possible, the analysis time step is set to 81 steps for a total analysis time of 27 h, which is 20 min for one iterative step.

Calculation results and analysis

Comparison of GEO calculation results with JA2 calculation results

The transient stability of slopes under rainfall conditions was analysed using the JA2 program in Chen and Chen's (2001) study. The water content distribution field and the final factor of safety were obtained. In this paper, GEO was used to carry out the analysis according to the setting of Chen and Chen's (2001) study, and a comparison of the results is shown in Fig. 3. Figure 3a shows the water content distribution field calculated by GEO, and Fig. 3b shows the water content distribution field calculated by the JA2 program. Comparing the two calculations, it can be seen that the difference between the two is extremely small. Numerically the minimum moisture content calculated by GEO is slightly greater than that calculated by the JA2 program. This error may be caused by the initial moisture content field designation, and the difference in values is only 0.01.

A comparison of the safety factors calculated by GEO and JA2 is shown in Table 2. Table 2 shows that there is a large difference between the two in the initial safety factors. This is mainly due to the fact that the unsaturated soil strength

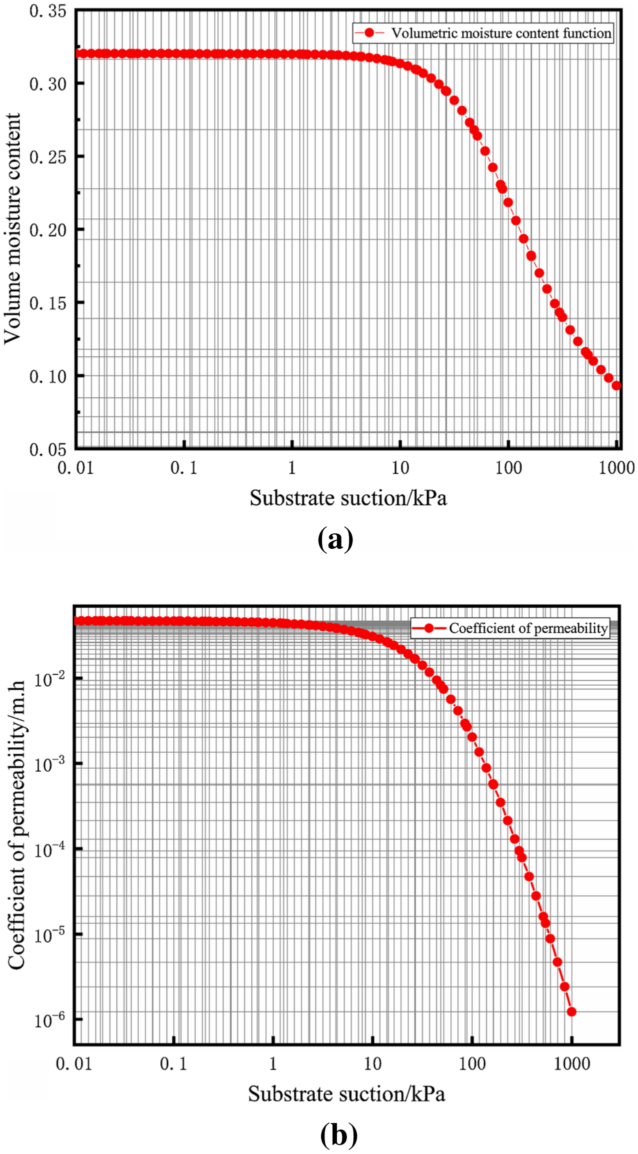


Fig. 2 Soil and water characteristics curve. **a** Volumetric moisture content function. **b** Permeability coefficient function

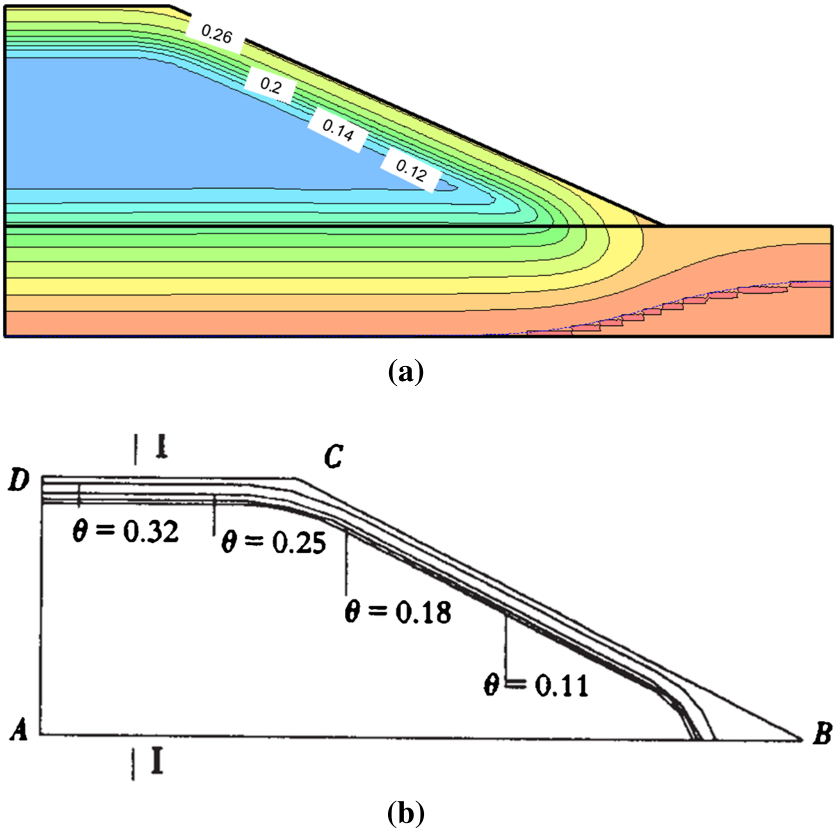


Fig. 3 Comparison of water content field distribution between GEO and JA2. **a** Water content distribution field from GEO calculations. **b** Water content distribution field from JA2 calculation

function set by the JA2 program is not the same as the function used by GEO. The difference between the functions defined in the initial state calculation will result in deviations in the stability of the initial stability coefficients, while the difference in the final stability is less. This phenomenon indicates that although there is a difference in the definition of the functional strength between the two. However, the differences in the analytical results of the final stability are relatively small and within tolerable limits.

Figure 4 gives the final slip surface comparisons obtained from the analysis of the GEO and JA2 programs. It can be seen from Fig. 4 that the final landslide surfaces calculated by both the GEO and JA2 programs show typical shallow landslide characteristics, but there are some differences between the GEO and JA2 landslide surfaces at the foot of the slope. This is mainly due to the fact that the JA2 program does not consider the influence of the second layer of soil on the foot of the slope. Although the strength of the second soil is set higher in GEO to avoid the influence of the second layer on the stability, but the influence of the seepage field cannot be eliminated. However, from a practical engineering point of view,

Table 2 Comparison of stability coefficients calculated by GEO and JA2

Calculation method	GEO	JA2	Percentage deviation
Initial stability factor	1.798	2.48	27%
Final stability factor	0.838	0.89	5.8%

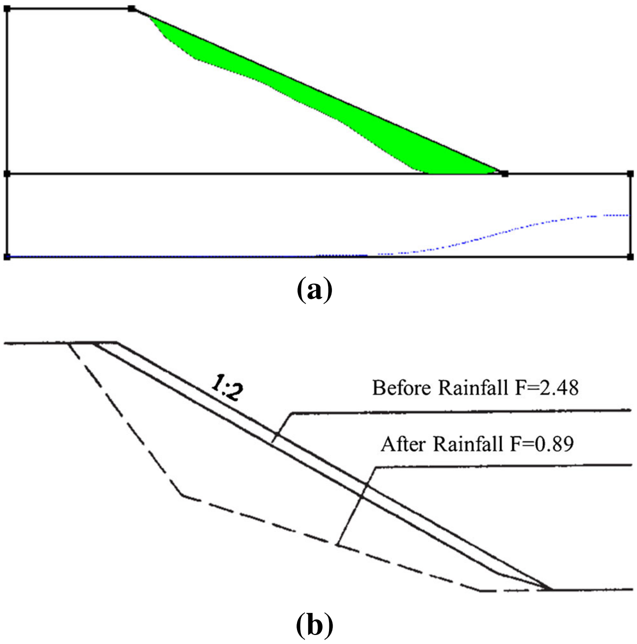
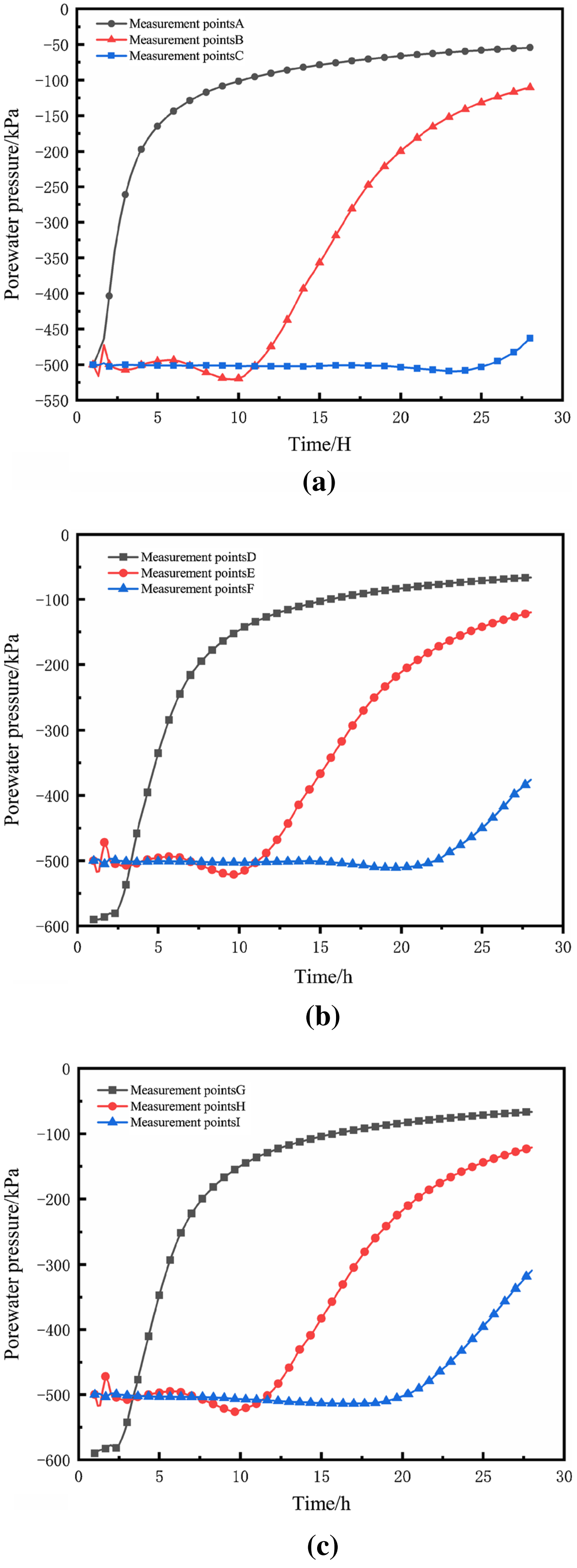


Fig. 4 Final slip surface ratio calculated by GEO and JA2. **a** Final slip surface calculated by GEO. **b** Final slip surface calculated by JA2



(a)

(b)

(c)

Fig. 5 Pore pressure variation curves at different locations. **a** Pore pressure variation curves at measurement points in the top of the slope. **b** Pore pressure variation curves at measurement points in the middle of the slope. **c** Pore pressure variation curve at each measurement point in the bottom of the slope

GEO's calculations are more in line with the actual engineering situation.

Therefore, from the above analysis, it is clear that the transient stability analysis of slopes under rainfall conditions using the GEO program is in very high agreement with the method proposed by Chen and Chen (2001) in terms of calculation results. The coupled flow-solid analysis of SEEP-SIGMA-SLOP using the GEO software is fully realisable for the slope instability process under rainfall conditions considering the strength attenuation of unsaturated soils due to rainfall infiltration.

Pore pressure variation at measurement points calculated by GEO

The variation pattern of pore pressure at different locations is shown in Fig. 5. As it is clear from Fig. 5, the variation of pore pressure at different locations at the same depth is basically the same. The change in pressure at the top of the slope is only slightly smaller than the change in pressure at the middle and foot of the slope at the same depth. In general, there are the following patterns.

(1) The shallower the depth, the greater the variation in pore pressure and the greater the influence of rainfall. Shallow soils will stabilise in about 5 h and medium and deep soils in about 20 h.
(2) The middle soils at different locations start to be affected by the rainfall at around 10 h. The deeper soils are affected around 20 h (slightly slower at the top of the slope at around 25 h).

The variation in pore pressure in the deep soils at the top of the slope is very small.

The above pattern indicates that the variation in pore pressure at different locations and at different depths is somewhat different in detail, although there is a certain regularity. This may be due to differences in slope infiltration at different locations. It should also be noted that the variation in pore pressure at the top of the slope is very small, which means that the strength of the soil at this location is also less attenuated. The final slip surface condition in Fig. 4 shows that the depth of the slip surface at the top of the slope is indeed shallow.

Variation in moisture content and shear strength at each measurement point calculated by GEO

A comparison of the water content and the shear strength of the soil at different locations is shown in Fig. 6. As can be seen from Fig. 6, the variation in soil moisture content and the variation in shear strength show a one-to-one correspondence. This indicates that the strength of the soil varies with the infiltration of rainfall in the GEO calculations. In other words, this calculation process enables the analysis of slope instability due to changes in soil strength caused by rainfall infiltration to be considered.

Slope stability analysis

The curve of slope safety factors with time is shown in Fig. 7. From Fig. 7, it can be seen that the change of slope safety factors with rainfall time can be roughly divided into three stages: the initial stable stage, the middle rapid decline stage and the final stable stage. In the first 5 h of rainfall, the slope is basically stable; from 5 to 15 h, the slope safety factor starts to decline rapidly; from 15 to 25 h, the safety factor is still decreasing but the magnitude is gradually levelling off. This means that the slope stability decreases significantly when the depth of rainfall infiltration reaches a threshold. The threshold value is determined in relation to the infiltration factors and the time of rainfall.

Figure 8 compares the difference between the safety factors calculated by the simplified Janbu method and the Morgenstern-Price method. From Fig. 8, it can be seen that the difference in the stability factors calculated by the two methods is very small. This indicates that there is no significant variation in the results of the transient stability analysis calculations, regardless of the calculation theory used.

Summary

In summary, the use of GEO for transient stability analysis of slopes under rainfall conditions is fully feasible. The difference between the results of the JA2 calculations presented in Chen and Chen's (2001) study is small. At the same time, the GEO calculation analysis is able to observe and analyse different locations of measurement points at different times during the rainfall process. The applicability and reliability of GEO is better than of Chen and Chen's (2001) study.

Grey-scale correlation sensitivity analysis

There are many factors influencing slope instability. In quantitative analysis, the values of each parameter are characterised by uncertainty, ambiguity, and randomness (Liu and Feng 2005). Therefore, it is necessary to carry out quantitative sensitivity analysis on the factors influencing the stability of slopes. At present, there are many methods for sensitivity analysis of slope stability, such as orthogonal design method (Ni et al. 2002), Monte Carlo method (Guo et al. 2018) and grey-scale correlation method (Chen and Jian 2006; Fu et al. 2011; Jiang et al. 2007; Wang et al. 2004). Among the many analytical theories, the grey-scale correlation method provides a relatively accurate description of the relationship between the influencing factors and the target influence values with relatively limited information. Therefore, this paper adopts the grey-scale correlation method to quantitatively study the sensitivity effects of different parameter changes on the slope stability factors caused by the rainfall process. The specific steps are as follows.

Grey-scale correlation theory

Step 1: Determine the comparison matrix and the reference matrix

The factors influencing the transient stability of slopes (in this paper, c', φ', k, γ, rainfall intensity and rainfall duration are the main factors to be considered) are selected as subseries to create a comparison matrix X.

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_i \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & L & x_{1i} \\ x_{21} & x_{22} & L & x_{2j} \\ M & M & O & M \\ x_{i1} & x_{i2} & L & x_{ij} \end{bmatrix} \tag{7}$$

The slope stability factors calculated under the conditions of the corresponding values of each subseries are selected as the parent series Y to build the reference matrix.

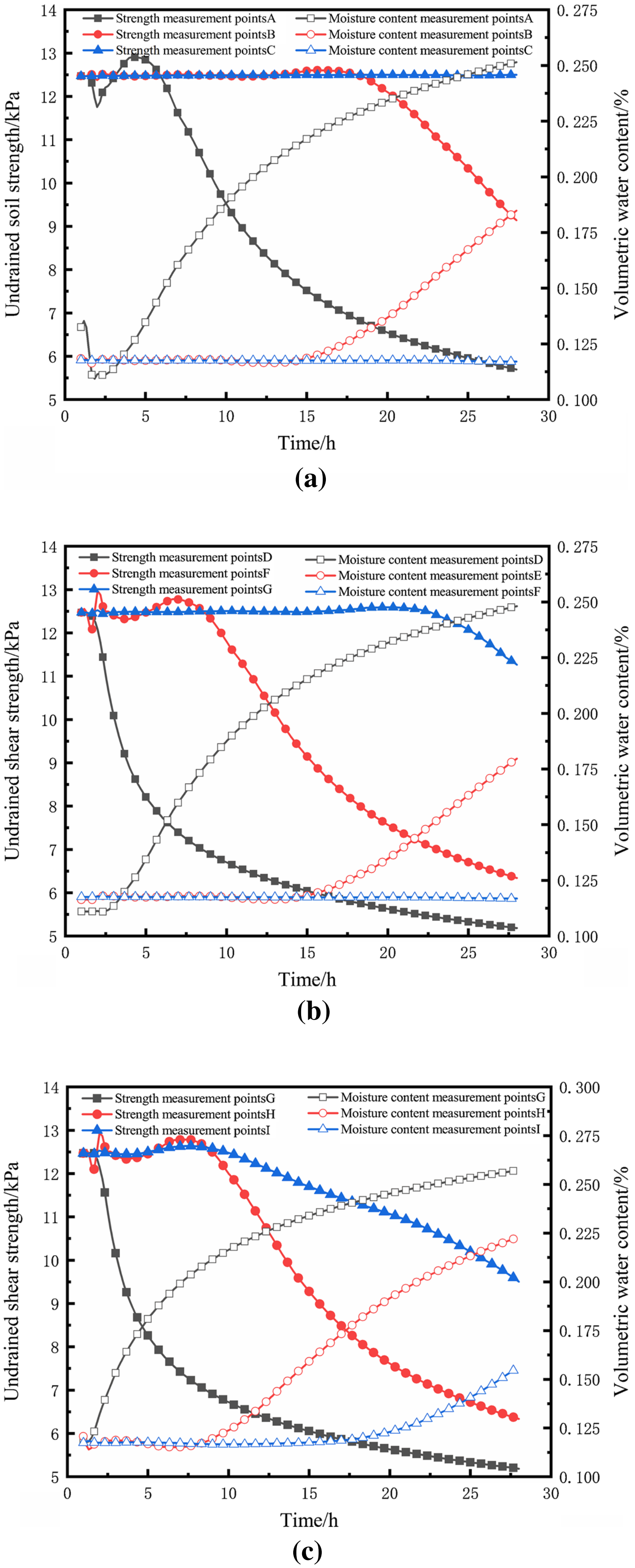
$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_i \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & L & y_{1i} \\ y_{21} & y_{22} & L & y_{2j} \\ M & M & O & M \\ y_{i1} & y_{i2} & L & y_{ij} \end{bmatrix} \tag{8}$$

Step 2: Matrix dimensionlessness

Matrix dimensionless normalisation is the most critical step in grey-scale correlation analysis. The main purpose of this step is to eliminate the effects of variability in the parameters. Therefore the above matrix needs to be normalised.

$$\begin{aligned} X_i' &= \left[X_i'(1), X_i'(2), LX_i'(n)\right] \\ X_i'(j) &= \frac{X_i(j) - \min X_i'(j)}{\max X_i(j) - \min X_i(j)} \\ X_i' &= \left[X_i'(1), X_i'(2), LX_i'(n)\right] \\ Y_i'(j) &= \frac{Y_i(j) - \min Y_i'(j)}{\max Y_i(j) - \min Y_i(j)} \end{aligned} \tag{9}$$

Fig. 6 Variation in moisture content and shear strength at different locations. **a** Variation in moisture content and shear strength at each measurement point at the top of the slope. **b** Variation in moisture content versus shear strength at each measurement point at the middle of the slope. **c** Variation in moisture content versus shear strength at each measurement point at the bottom of the slope



(a)

(b)

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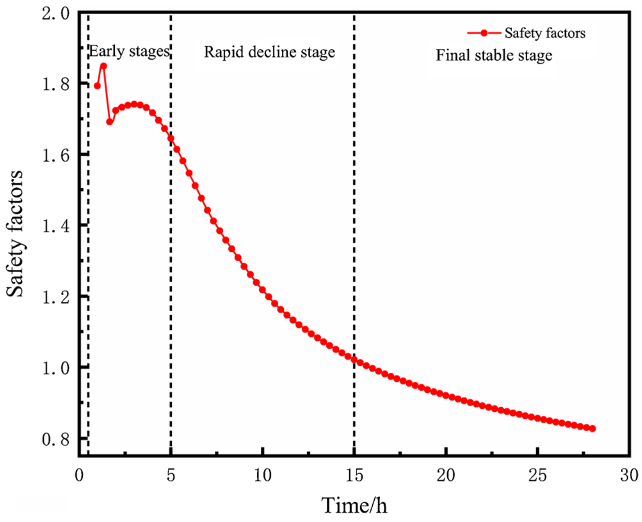

Fig. 7 Factor of safety curve over time

Step 3: Create a variance matrix

The variance matrix Δ was obtained from the normalised X, Y series by making the following changes.

$$\Delta ij = \left| x'_{ij} - y'_{ij} \right| \tag{10}$$

Take its maximum and minimum values:

$$\begin{aligned} \Delta_{\max} &= \max(\Delta_{ij}) \\ \Delta_{\min} &= \min(\Delta_{ij}) \end{aligned} \tag{11}$$

Step 4: Build the grey-scale correlation coefficient matrix

The grey-scale correlation coefficient matrix is calculated according to the variance matrix in the following way:

$$C_{ij} = (\Delta_{\min} + \mu\Delta_{\max}) / (\Delta_{ij} + \mu\Delta_{\max}) \tag{12}$$

where μ is the resolution factor taken as 0.5 in this paper.

Step 5: Solving for correlation D_i

The correlation D_i is calculated as follows.

$$D_i = \frac{1}{n} \sum_{j=1}^{n} C_{ij} \tag{13}$$

The higher the value of the correlation D_i, the greater the influence of the factor on the target value, which means the greater the sensitivity.

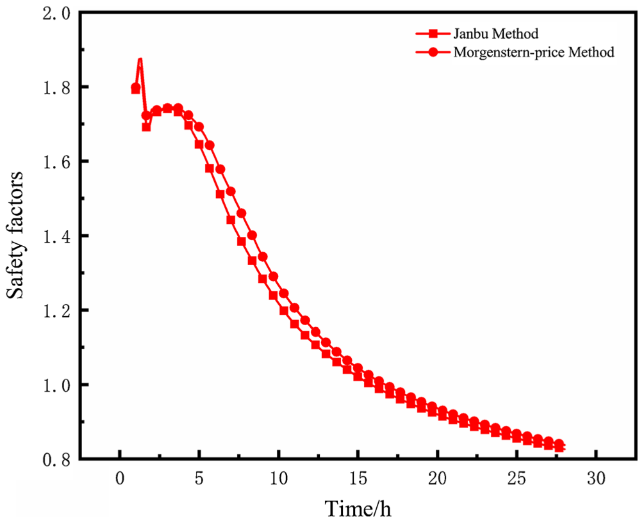

Fig. 8 Comparison of the curves of the Janbu method and the M-P method for calculating the safety factor over time

Sensitivity analysis

The factors affecting the transient stability of slopes under rainfall conditions can be broadly classified into three categories: (i) the physical and mechanical properties of the slope soil (cohesion, angle of internal friction, permeability factors, etc.), (ii) external environmental conditions (rainfall intensity, rainfall calendar time, etc.) and (iii) topographic and geomorphological conditions (slope height, slope ratio, etc.). In this paper, we mainly consider the physical and mechanical properties of soil materials and the influence of external conditions. The parameters taken from Chen and Chen's (2001) study are used as the base values to consider the influence of changes in c', φ', k, γ, rainfall intensity (P) and rainfall duration (H) on stability. The specific values taken for each parameter variation and the corresponding stability factors F are shown in Table 3.

The comparison matrix and reference matrix are created from Table 3 according to Eqs. (7) and (8) as follows.

$$X = \begin{bmatrix} \gamma \\ C' \\ \varphi' \\ K \\ P \\ H \end{bmatrix} = \begin{bmatrix} 13.2 & 16.2 & 19.2 & 22.2 \\ 7.01 & 12.01 & 17.01 & 22.01 \\ 9.06 & 14.06 & 19.06 & 24.06 \\ 0.042 & 0.037 & 0.032 & 0.027 \\ 300 & 240 & 180 & 120 \\ 32 & 37 & 42 & 47 \end{bmatrix}$$

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_5 \\ Y_6 \end{bmatrix} = \begin{bmatrix} 0.990 & 0.837 & 0.728 & 0.649 \\ 1.443 & 2.034 & 2.636 & 3.237 \\ 1.567 & 2.324 & 3.115 & 3.954 \\ 0.828 & 0.815 & 0.795 & 0.775 \\ 0.905 & 0.989 & 1.096 & 1.246 \\ 0.796 & 0.763 & 0.734 & 0.708 \end{bmatrix}$$

The above matrix is polarised by both Eqs. (9) and (10) to obtain the difference matrix Δ as follows.

Table 3 Calculation of stability factors under different factor variations

Severe γ/(kN.h^{-3})	F	Cohesion $C^{'}$/(kPa)	F	Internal friction angle/$\varphi^{'}$(°)	F	Permeability factor K/(m.h^{-1})	F	Rainfall intensity/(m.h^{-1})	F	Duration of rainfall/h	F
13.2	0.99	7.01	1.443	9.06	1.567	0.042	0.828	300	0.905	32	0.796
16.2	0.837	12.01	2.034	14.06	2.324	0.037	0.815	240	0.989	37	0.763
19.2	0.728	17.01	2.636	19.06	3.115	0.032	0.795	180	1.096	42	0.734
22.2	0.649	22.01	3.237	24.06	3.954	0.27	0.775	120	1.246	47	0.708

$$\Delta = \begin{bmatrix} 0.4902 & 0.1297 & 0.1759 & 0.4440 \\ 0.1342 & 0.0425 & 0.0446 & 0.1321 \\ 0.0248 & 0.0009 & 0.0141 & 0.0098 \\ 0.1866 & 0.0578 & 0.0622 & 0.1822 \\ 0.5740 & 0.2090 & 0.1778 & 0.6052 \\ 0.2509 & 0.0803 & 0.0850 & 0.2462 \end{bmatrix}$$

Based on the above differentiation matrix, the grey-scale correlation coefficient matrix is calculated according to Eq. (12).

$$L = \begin{bmatrix} 0.3828 & 0.7020 & 0.6342 & 0.4064 \\ 0.6947 & 0.8794 & 0.8740 & 0.6981 \\ 0.9269 & 1.0000 & 0.9582 & 0.9713 \\ 0.6203 & 0.8419 & 0.8319 & 0.6259 \\ 0.3462 & 0.5932 & 0.6317 & 0.3343 \\ 0.5483 & 0.7925 & 0.7830 & 0.5529 \end{bmatrix}$$

Finally, the correlation D_i is calculated based on the grey-scale correlation coefficient matrix according to Eq. (13).

$$D_i = [0.5313 \ \ 0.7865 \ \ 0.9640 \ \ 0.7299 \ \ 0.4763 \ \ 0.6691]$$

It can be seen that the factors affecting the stability factors of slopes under rainfall transient stability analysis in order of sensitivity are internal friction angle φ > cohesion C' > infiltration coefficient K > rainfall duration H > heaviness γ > rainfall intensity P. Among the six factors selected, the angle of internal friction φ is the most sensitive, with a correlation value of over 9.6, followed by cohesion C' and infiltration coefficient K with a correlation value of over 7.2. The least influential factors are rainfall duration H, heaviness γ and rainfall intensity P.

The greatest influence of internal friction on slope stability is due to the fact that when the shallow soil is saturated, the value of the cohesive force C' decays to a very low state, and the sliding of the slope is then close to a state of pure friction. The sliding of the slope is mainly limited by the angle of internal friction, and the expression of the safety factor can be approximated by the following formula.

$$F_S = \frac{\tan\phi}{\tan\alpha} \tag{14}$$

From the calculation of Eq. (14), it can be seen that the slope safety factor at this point is mainly controlled by the angle of internal friction. Therefore, from the above analysis, it can be seen that the angle of internal friction has the greatest influence on the transient stability of unsaturated soil slopes under rainfall infiltration conditions.

Conclusions

(1) The analysis of transient stability of slopes under rainfall conditions by means of GEO finite elements is fully feasible. The calculated results do not differ much from those of Chen and Chen's (2001) study. Moreover, GEO is able to plot various parameter variation curves based on the calculated results for different locations and depths of measurement points, which makes it more applicable.

(2) Comparing the stability calculation results of the simplified Janbu method with those of the M-P method, it can be seen that there is little difference between the safety factors calculated by the different stability factor calculation methods.

(3) The sensitivity analysis based on the grey-scale correlation analysis shows that the factors affecting its stability factors in order of sensitivity are internal friction angle φ > cohesion C' > infiltration coefficient K > rainfall ephemeris H > heaviness γ > rainfall intensity P. The angle of internal friction has the greatest influence on landslides. This is mainly due to the significant attenuation of soil cohesion caused by rainfall, and the sliding of shallow soil is mainly controlled by the angle of internal friction.

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Declarations

Conflict of interest The author declares that he has no competing interests.

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