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Effect of drag force on stability of residual soil slopes under surface runoff

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ABSTRACT

To investigate the effect of drag force on stability of residual soil slopes, a modified approach based on the limit equilibrium method is proposed by establishing a nonlinear coupled mathematical model to calculate the seepage velocities in soils and the runoff velocities at a fluid–solid interface. In this mathematical model, the Navier–Stokes equation and Brinkman-extended Darcy equation are used to describe the incompressible surface runoff and seepage in soils, respectively. Then, the drag force can be derived by adopting Newton’s law of internal friction, and the factor of safety (FOS) of residual soil slopes considering drag force can be calculated based on the limit equilibrium method. The modified approach was applied to analyse the stability of rainfall-induced landslides in residual soils in Nanjiang, Sichuan, China, 2011. We found that the runoff depth can significantly control the FOS of the residual soil slopes and cause slope failures. The results of sensitivity analysis highlight the significance for considering drag force due to surface runoff when calculating the FOS of the residual soil slope. The FOS obtained from the modified approach is more reasonable, and this modified approach also can be used for evaluating or predicting rainfall-induced slope instability in residual soils.

KEYWORDS

Drag force; factor of safety; residual soil slopes

Introduction

Landslides constitute a major threat to both lives and property worldwide especially in regions of residual soil subject to heavy rainfall. Although slope failures may develop due to many factors, such as earthquakes, human-induced factors including the loading of the slope or excavation for construction purposes, the occurrence of landslides in residual soils is mainly attributed to rainfall (Brand 1981, 1984; Fredlund and Rahardjo 1994; Lim et al. 1996; Rahardjo et al. 1996; Tsukamoto 1998; Montrasio and Valentino et al. 2009; Cho 2015). Furthermore, most of the rainfall-induced landslides in residual soils consist of relatively shallow slips above the groundwater table with the thickness of sliding mass smaller than 5 m approximately, and slide along the interface between the soil layer and underlying bedrock (Lim and Rahardjo 1996; Montrasio and Valentino 2009).

For example, 1162 rainfall-induced landslides in residual soils occurred in Nanjiang, China during the rainfall on 17–18 September 2011. All of these rainfall-induced landslides were shallow landslides with the thickness of sliding mass smaller than 5 m (Zhang 2016). More recently, the
Guangming landslide occurred in industrial estate of Shenzhen City, in China on 20 December 2015, caused 73 deaths and damaged 33 buildings with direct economic losses up to 881 million RMB (Xu 2016). This is another representative case study related to rainfall-induced landslides in loose deposits. Therefore, whether many widespread rainfall-induced landslides or a single large-scale landslide have a severe threat to the safety of densely populated area, such as the large number of landslides event in Nanjiang country and the Guangming landslide in Shenzhen City mentioned above. Slope stability problem in residual soils should be thus paid more high attention.

It is generally recognized that rainfall-induced landslides in soil slopes are caused by increased pore pressures and seepage forces during periods of intense rainfall (Terzaghi 1950; Sidle and Swanson 1982; Matsuura et al. 2008; Xia and Ren et al. 2013, 2015). It is the increased pore pressure that decreases the effective stress in the soil and thus reduces the soil shear strength, eventually resulting in slope failure (Brand 1981, 1984; Brenner et al. 1985; Montrasio et al. 2009; Liu and Rong et al. 2015). Terzaghi (1950) first presented that rainfall-induced landslides are caused by increased pore pressures and seepage forces during periods of intense rainfall. Cho (2015) found that the infiltration of rainwater will significantly reduce the matric suction of unsaturated soil and the anti-slide force, thus causing slope failures. Matsuura and Wang proposed that most shallow landslides are induced by the change of transient pore water pressure due to short-term concentrated rainfalls (Matsuura 2008; Wang and Sassa 2009).

Unfortunately, the drag force at a fluid–solid interface is generally ignored in the previous studies when calculating the stability of residual soil slopes under surface runoff. In 1851, Wilson (2013) presented the analytic solution of drag force for a ball under the slow movement in an infinite viscous fluid. Rumer and Drinker (1966) verified Darcy’s law in linear laminar flow by adopting Stokes’ formula of drag force. On the basis of cubic law, Chai derived the equations of drag force on the single fracture rock wall surface (Chai 2006).

In the present study, a modified approach based on the limit equilibrium method is proposed to investigate the effect of drag force on stability of residual soil slopes by establishing a nonlinear coupled mathematical model to calculate the seepage velocities in soils, runoff velocities as well, and ultimately calculating the drag force at a fluid–solid interface by adopting Newton’s law of internal friction. This modified approach was applied to analyse the stability of rainfall-induced landslides in residual soils in Nanjiang, Sichuan, China, in 2011. Several key factors, including the runoff depth, the thickness of sliding mass, the angle of slip surface as well as the friction angle and cohesion of soil, were utilized for the sensitivity analysis to evaluate the effect of drag force on stability of residual soil slopes under surface runoff.

**Calculation of flow field**

**Theoretical model**

The surface runoff due to rainfall or meltwater often leads to the scouring effect on the soil slopes. This scouring effect becomes more strong with the increase of flow intensity, and has a potential threat to the slope stability. To investigate the effect of drag force on stability of residual soil slopes under surface runoff, a seepage model considering surface runoff was established (see Figure 1). In the model, \( \theta \) is the slope angle; \( L, b, n \) and \( K \) are the length, thickness, porosity and permeability of soils, respectively; \( h \) is the runoff depth. The coordinate system was set up, as shown in Figure 1. \( v_x \) and \( u_x \) are seepage velocity in soils and runoff velocity at a fluid–solid interface in the \( x \) direction, respectively.

In fact, the movement of fluids is a three-dimensional space movement, and its influencing factors are very complicated. To simplify, the following assumptions are proposed:

1. runoff extend infinitely along the \( x \) direction;
2. the soil is homogeneous;
(3) the water flow is a two-dimensional plane motion, namely, the flow velocity is 0 in the y direction;
(4) the water flow is the laminar flow of Newton Fluid;
(5) the fluid is incompressible and satisfies the continuity equation;
(6) the underlying rock is impermeable;
(7) the seepage in soils satisfies the Brinkman-extended Darcy equation:

\[ n pf - n \nabla \bar{p} + \eta \nabla^2 \bar{\nu} - n \frac{\eta}{K} \bar{\nu} = \frac{\rho}{n} (\bar{\nu} \cdot \nabla) \cdot \bar{\nu} \]  

where \( \bar{\nu} \) is the seepage velocity in soils (LT\(^{-1}\)); \( \bar{p} \) is the fluid pressure (ML\(^{-1}\)T\(^{-2}\)); \( \eta \) is the kinematic viscosity of water (ML\(^{-1}\)T\(^{-1}\)); \( \rho \) is the density of water (ML\(^{-3}\)); \( f \) is the mass force (MLT\(^{-2}\)); \( n \) is the porosity of soils (dimensionless); \( K \) is the permeability of soils (L\(^2\)); \( g \) is the gravitational acceleration; \( (\bar{\nu} \cdot \nabla) \) is the migration derivative, \( \nabla \) is the Hamilton operator.

The surface runoff can be described by the Navier–Stokes equation:

\[ f - \nabla \bar{p} + \eta \nabla^2 \bar{u} = \rho_w (\bar{u} \cdot \nabla) \cdot \bar{u} \]  

where \( \bar{u} \) is the runoff velocity (LT\(^{-1}\)), and other parameters are the same as above.

**Derivation of runoff velocity**

According to the above assumptions, the water flows of surface runoff satisfy the continuity equation and Navier–Stokes equation.

The continuity equation is written as follows:

\[ \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \]  

where \( u_y \) and \( u_z \) are seepage velocities in soils in the \( y \) and \( z \) directions, respectively (LT\(^{-1}\)).
The Navier–Stokes equation (in the \( x \) direction) is written as follows:

\[
f_x - \frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) = \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z}
\]

(4)

where \( f_x \) is the mass force in the \( x \) direction (ML\(^{-2}\)); \( P \) is fluid pressure in the \( x \) direction (ML\(^{-1}\)T\(^{-2}\)); \( \nu \) is coefficient of kinematic viscosity of water (L\(^2\)T\(^{-1}\)); \( y \) is coefficient of kinematic viscosity of water (L\(^2\)T\(^{-1}\)); \( y = h/r \).

As the runoff velocities are zero in the \( y \) and \( z \) directions, namely, \( u_y = u_z = 0 \), so \( \partial u_y/\partial x = \partial u_z/\partial x = 0 \). Substituting it into Equation (3), \( \partial u_y/\partial x = 0 \) can be obtained. As \( u_x \) is constant in the \( z \) direction, namely, \( \partial u_x/\partial z = 0 \). In the \( x \) direction, \( f_x = g \sin \theta \), \( \partial P/\partial x = -\Delta P/L \). As the runoff is constant flow, so \( \partial u_x/\partial t = 0 \). Substituting these conditions into Equation (4), Equation (5) can be obtained as follows:

\[
\eta \frac{d^2 u_x}{dy^2} + \frac{\Delta P}{L} + \gamma_w \sin \theta = 0
\]

(5)

where \( \gamma_w \) is unit weight of water (ML\(^{-2}\)T\(^{-2}\)).

Solving Equations (5), the runoff velocity can be obtained as follows:

\[
u_x = -\frac{\Delta P + \gamma_w L \sin \theta}{2\eta L} y^2 + A_1 y + A_2
\]

(6)

where \( A_1 \) and \( A_2 \) are undetermined parameters.

**Derivation of seepage velocity**

According to the assumptions of analytic model, the water flows in soils satisfy the continuity equation and Brinkman-extended Darcy equation.

The continuity equation is written as follows:

\[
\frac{\partial v_y}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0
\]

(7)

where \( v_y \) and \( v_z \) are seepage velocities in soils in the \( y \) and \( z \) directions (LT\(^{-1}\)), respectively.

The Brinkman-extended Darcy equation (in the \( x \) direction) is expressed as follows:

\[
\eta f_x - n \frac{\eta}{K} v_x - n \frac{\partial p}{\partial x} + \eta \left( \frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2} \right) = \rho \left( \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z} \right)
\]

(8)

While the saturated stable seepage is assumed, the seepage velocities in soils in the \( y \) and \( z \) directions can be treated as zero due to impermeability of rock. Namely, \( v_y = v_z = 0 \), so \( \partial v_y/\partial y = \partial v_z/\partial z = 0 \). Then, substituting it into Equation (7), \( \partial v_y/\partial x = 0 \) can be obtained. Meanwhile, \( v_x \) is constant in the \( z \) direction, so \( \partial v_x/\partial z = 0 \). In the \( x \) direction, \( f_x = g \sin \theta \), \( \partial P/\partial x = -\Delta P/L \). As seepage is constant flow, \( \partial v_x/\partial t = 0 \). Substituting these conditions into Equation (8), Equation (9) can be obtained as follows:

\[
\frac{d^2 v_x}{dy^2} - n \frac{\partial v_x}{K} + n \frac{\Delta P}{\eta L} + n \frac{\gamma_w \sin \theta}{\eta} = 0
\]

(9)
Solving Equations (9), Equation (10) can be obtained as follows:

\[ v_x = B_1 e^{\sqrt{n}h} + B_2 e^{-\sqrt{n}h} + \frac{(\Delta P + \gamma_w L \sin \theta)K}{\eta L} \]  

(10)

where \( B_1 \) and \( B_2 \) are undetermined parameters.

**Calculation of runoff velocity and seepage velocity**

Both the runoff velocity \( u_x \) and the seepage velocity \( v_x \) satisfy the following boundary conditions:

1. the maximum runoff velocity is at \( y = h \), so \( du_x/\text{dy} = 0 \);
2. the runoff velocity \( u_x \) is equal to the seepage velocity \( v_x \) at \( y = 0 \), and the shear stress is continuous (Neale and Nader 2009), that is, \( v_x = u_x \) and \( \frac{dv_x}{\text{dy}} = \frac{du_x}{\text{dy}} \);
3. the seepage velocity \( v_x \) is zero at \( y = -b \), namely, \( v_x = 0 \).

Substituting these boundary conditions into Equations (6) and (10), the undetermined parameters \( A_1, A_2, B_1 \) and \( B_2 \) can be thus derived as shown in the following equation:

\[
\begin{cases}
A_1 = \frac{(\Delta P + \gamma_w L \sin \theta)h}{\eta L} \\
A_2 = \frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} + K)}{\eta L} \\
B_1 = \frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} - Ke^{-b/\sqrt{n}})}{\eta L(e^{-2b/\sqrt{n}} + 1)} \\
B_2 = -\frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} + K)}{\eta L(e^{2b/\sqrt{n}} + 1)} \;
\end{cases}
\]

(11)

Therefore, the runoff velocity \( u_x \) and the seepage velocity \( v_x \) can be obtained as follows:

\[
u_x = \frac{\Delta P + \gamma_w L \sin \theta}{2\eta L} y^2 + \frac{(\Delta P + \gamma_w L \sin \theta)h}{\eta L} y + \frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} + K)}{\eta L}
\]

(12)

\[
v_x = \frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} - Ke^{-b/\sqrt{n}})}{\eta L(e^{-2b/\sqrt{n}} + 1)} e^{\sqrt{n}/K} - \frac{(\Delta P + \gamma_w L \sin \theta)(h/\sqrt{nK} + Ke^{b/\sqrt{n}})}{\eta L(e^{2b/\sqrt{n}} + 1)} e^{-\sqrt{n}/K} + \frac{(\Delta P + \gamma_w L \sin \theta)K}{\eta L}
\]

(13)

As \( \Delta P = \gamma_w \Delta H \) and \( \Delta H/L = i, i = \tan \theta \), where \( i \) is the hydraulic gradient and \( \Delta H \) is the difference in water head, therefore, Equations (12) and (13) can be rewritten as follows:

\[
u_x = -\frac{\gamma_w (\sin \theta + \tan \theta)}{2\eta} y^2 + \frac{\gamma_w h (\sin \theta + \tan \theta)}{\eta} y + \frac{\gamma_w (h/\sqrt{nK} + K)(\sin \theta + \tan \theta)}{\eta}
\]

(14)
\[
\nu_x = \frac{\gamma_w \left( h\sqrt{nK} - Ke^{-b\sqrt{n}/K} \right) (\sin\theta + \tan\theta) e^{\sqrt{n}/K}}{\eta (e^{-2b\sqrt{n}/K} + 1)} - \frac{\gamma_w \left( h\sqrt{nK} + Ke^{b\sqrt{n}/K} \right) (\sin\theta + \tan\theta) e^{-\sqrt{n}/K}}{\eta (e^{2b\sqrt{n}/K} + 1)} + \frac{\gamma_w K (\sin\theta + \tan\theta)}{\eta} \tag{15}
\]

**Shear stress derived based on Newton’s law of internal friction**

According to Newton’s law of internal friction, the shear stress acting on the slope surface due to runoff can be expressed as follows:

\[
\tau = \eta \frac{du}{dy} \tag{16}
\]

where \( \tau \) is shear stress \((ML^{-1}T^{-2})\) and \( u \) is the runoff velocity \((LT^{-1})\).

Substituting the runoff velocity \( u_x \) into Equation (16), the shear stress \( \tau_x \) in the \( x \) direction can be derived:

\[
\tau_x = \gamma_w (\sin\theta + \tan\theta) (-y + h) \tag{17}
\]

At the position of \( y = 0 \), the shear stress \( \tau_s \) acting on the slope due to surface runoff can be expressed as follows:

\[
\tau_s = \gamma_w h (\sin\theta + \tan\theta) \tag{18}
\]

As can be seen from Equation (18), the shear stress \( \tau_s \) is mainly dominated by the runoff depth \( h \) as well as the slope angle \( \theta \), and increases with the increase of the value of \( h \) and \( \theta \).

**Calculation of safety factor considering drag force**

Force analysis of slope stability is shown in Figure 2. These forces directly acting on the soil layer include gravity \( G \), buoyancy \( F_b \), normal force \( F_N \), drag force \( F_D \), seepage force \( G_D \) and frictional resistance \( F_f \).

\( G \) can be derived by the following formula:

\[
G = bL\gamma_s \tag{19}
\]

where \( \gamma_s \) is the unit weight of soil \((ML^{-1}T^{-2})\).

\( F_b \) can be expressed as follows:

\[
F_b = bL\gamma_w \tag{20}
\]

\( F_N \) can be expressed as follows:

\[
F_N = (G - F_b)\cos\theta \tag{21}
\]

\( F_f \) can be expressed as follows:

\[
F_f = F_N \tan\varphi + cL = (G - F_b)\cos\theta \tan\varphi + cL \tag{22}
\]

where \( \varphi \) is the friction angle of soil.
Substituting Equations (19) and (20) into Equation (22), $F_f$ can be rewritten as follows:

$$F_f = bL(\gamma_s - \gamma_w)\cos\theta \tan \phi + cL \tag{23}$$

Therefore, $F_D$ can be derived as follows:

$$F_D = L\tau_s \tag{24}$$

where $\tau_s = \gamma_w h (\sin\theta + \tan\theta)$.

The seepage force $G_D$ can be written as follows:

$$G_D = i\gamma_w L \tag{25}$$

Based on the limit equilibrium method, the factor of safety (FOS) $K_s$ is thus obtained:

$$K_s = \frac{F_f + F_b \sin \theta}{F_D + G_D + G \sin \theta} \tag{26}$$

As can be seen from Equation (26), the drag force is an unfavourable factor for slope stability. The greater the drag force $F_D$, the lower the FOS $K_s$.

**Application**

Rainfall-induced landslides in residual soil slopes: case studies in the Nanjiang area of China

One thousand one hundred and sixty-two rainfall-induced landslides occurred in Nanjiang, Sichuan, China on 17–18 September 2011. From 6 to 15 September 2011, a total cumulative rainfall of 268.1 mm was recorded, and on 17 and 18 September, a total rainfall of 250.4 and 179.1 mm was recorded, respectively (Zhang 2016). The study area is covered by residual soils with a depth less than 5 m approximately. The underlying bedrock is mainly composed of thin layer mudstone of Jianmenguan Group in Cretaceous system, with attitude of $170^\circ \pm 12^\circ$. These rainfall-induced
landslides slid along the interface between the soil and underlying bedrock (Figure 3), with the thickness of sliding mass varying from 0.5 to 5 m approximately. Many extensive rainfall-induced landslides occurring in residual soils have a severe threat to the safety of densely populated villages during the intense rainfall season, just like landslides in Nanjiang area. Slope stability problem in residual soils should be thus paid more high attention. In this section, we take the representative landslide in Nanjiang area as an example to analyse the effect of drag force on stability of residual soil slope under surface runoff using the above proposed method. The idealized profile of the case study slope with pre-slide topography is shown in Figure 4.

**Parameters for sensitivity analysis of safety factor**

The parameters for sensitivity analysis of safety factor of the slope include runoff depth $h$, thickness of sliding mass $b$, angle of slip surface $\theta$, friction angle of soil $\varphi$ and cohesion of soil $C$. The parameters used for the sensitivity analysis of safety factor of the slope are summarized in Table 1. An assumed runoff depth varying from 0 to 0.3 m is included in the study. The thicknesses of sliding mass which were assumed in sensitivity analysis are 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 m. This range mainly covers most of the landslides in residual soils in terms of thickness of sliding mass. Likewise, the angle of slip surface is assumed to vary from 10° to 18° based on the attitude of strata in Nanjiang area. The friction angle and cohesion of soil are assumed to vary from 10° to 16° and from 0 to 10 kpa, respectively.

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*Figure 3.* Landslide slid along the interface between the soil and underlying bedrock in Nanjiang area (Zhang 2016).

*Figure 4.* The idealized profile of the case study slope with pre-slide topography.
Results

Figure 5 shows the FOS for an assumed thickness of sliding mass varying from 0.5 to 5 m. In the analysis for the runoff depth of 0 m and the thickness of sliding mass of 0.5 m, the FOS that was calculated is 1.04. If the runoff depth is 0.3 m and the thickness of sliding mass is 0.5 m, then the FOS drops to 0.83. For the runoff depth = 0 m and the thickness of sliding mass = 5 m, the FOS of the slope is 1.05. If the runoff depth is 0.3 m and the thickness of sliding mass is 5 m, then the FOS drops to 1.03. It means that if the thickness of sliding mass is relatively small, then the runoff depth would have the largest effect on the FOS. The FOS of the slope has a positive correlation with the variation of thickness of sliding mass, and decreases with the increase of the runoff depth.

Figure 6 shows the FOS of the slope with the different angle of slip surface varying from 10° to 18°. From Figure 6, it can be seen that different angle of slip surface can affect significantly the stability of residual soil slope. If the runoff depth is 0 m, the FOS of the slope drops from 1.19 to 0.83 when the angle of slip surface increases from 10° to 18°. For the runoff depth = 0.3 m, the FOS of the slope drops from 1.12 to 0.78 when the angle of slip surface increases from 10° to 18°. The results indicate that the effect of the angle of slip surface on stability of residual soil slope is greater than that of the runoff depth on stability of residual soil slope. For the same angle of slip surface, the greater the runoff depth, the lower the FOS of the slope.

Table 1. Summary of the parameters used for the sensitivity analysis of safety factor.

| Runoff depth (m) | 0   | 0.05 | 0.1  | 0.15 | 0.2  | 0.25 | 0.3  |
|------------------|-----|------|------|------|------|------|------|
| Thickness of sliding mass b (m) | 0.5 | 1.0  | 1.5  | 2.0  | 2.5  | 3.0  | 3.5  | 4.0  | 4.5  | 5.0  |
| Angle of slip surface θ (°) | 10  | 11   | 12²  | 13   | 14   | 15   | 16   | 17   | 18   |
| Cohesion of soil c (kPa) | 0   | 2    | 4    | 6    | 8    | 10   | 12   | 13   | 14²  | 15   | 16   |
| Friction angle of soil φ (°) | 10  | 11   | 12²  | 13   | 14²  | 15   | 16   | 17   | 18²  |
| Unit weight of soil γ_s (kN/m³) | 22.5 | 22.5² |
| Length of slip surface L (m) | 50² |

² The actual parameters of soils.

Figure 5. Sensitivity analysis of safety factor of slope while for an assumed thickness of sliding mass varying from 0.5 to 5 m, and for an assumed runoff depth varying from 0 to 0.3 m.
Figure 7 shows the FOS of the slope with the different friction angle of soil varying from 10° to 16°. From Figure 7, we can see that the FOS of the slope has a significant positive linear relationship with the friction angle of soil. In the analysis for the runoff depth of 0 m and the friction angle of 10°, the FOS that was calculated is 0.86. If the runoff depth is 0.3 m and the friction angle is 10°, then the FOS drops to 0.81. For the runoff depth = 0 m and the friction angle = 16°, the FOS of the slope is 1.15. If the runoff depth is 0.3 m and the friction angle is 16°, then the FOS drops to 1.08. In conclusion, for an assumed friction angle of soil, the FOS of the slope decreases approximately linearly with the increase of the runoff depth. The greater the runoff depth, the lower the FOS of the slope.
Figure 8 shows the FOS of the slope with variation of cohesion of soil varying from 0 to 10 kpa. The FOS of the slope has a positive linear correlation with the variation of cohesion of soil, and decreases with the increase of the runoff depth. If the cohesion of soil is 0 kpa, the FOS drops from 1.06 to 0.99 when the runoff depth increases from 0 to 0.3 m. Nevertheless, if the cohesion of soil is 10 kpa, the FOS drops from 2.01 to 1.89 when the runoff depth increases from 0 to 0.3 m. Consequently, for an assumed friction angle of soil, the FOS of the slope decreases with the increase of the runoff depth. The greater the runoff depth, the lower the FOS of the slope.

Discussion

Based on the results of the sensitivity analysis of safety factor, we found that the FOS is very sensitive to the thickness of sliding mass, the angle of slip surface as well as the friction angle and cohesion of soil. Moreover, the runoff depth can significantly control the FOS of the residual soil slope and cause slope failures. For instance, in the analysis for the thickness of sliding mass of 1 m, the FOS drops from 1.05 to 0.93 when the runoff depth increases from 0 to 0.3 m (see in Figure 5). In addition, Figure 6 demonstrates that the FOS drops from 1.05 to 0.99 when the angle of slip surface is 12° and the runoff depth increases from 0 to 0.3 m. Likewise, the FOS would be less than 1 with the increase of runoff depth also can be found in the results of sensitivity analysis for an assumed friction angle and cohesion of soil (see in Figures 7 and 8). The FOS has a negative correlation with the variation of runoff depth. The greater the runoff depth, the lower the FOS of the slope. The runoff depth plays a significant role in residual soil slope failure when the slope is in a critical stable state or close to a critical stable state. Furthermore, the results of the sensitivity analysis also explain the reason for occurrence of so many rainfall-induced landslides in residual soils in Nanjiang area during the rainfall on 17–18 September 2011.

Conclusion

In this research, to investigate the effect of drag force on stability of residual soil slopes, a modified approach based on the limit equilibrium method is proposed by establishing a nonlinear coupled mathematical model to calculate the seepage velocities in soils and runoff velocities, and ultimately
calculating the drag force on the basis of Newton’s law of internal friction. This modified approach was applied to analyse the stability of rainfall-induced landslides in residual soils in Nanjiang area of China.

The results show that the FOS of residual soil slopes is very sensitive to the thickness of sliding mass, the angle of slip surface as well as the friction angle and the cohesion of soil. Moreover, the runoff depth can significantly control the FOS and cause slope failures. The FOS has a negative correlation with the variation of runoff depth. The greater the runoff depth, the lower the FOS of the slope. The runoff depth plays a significant role in residual soil slope failure when the slope is in a critical stable state or close to a critical stable state. Moreover, the thinner sliding mass can lead to a large decrease of the FOS due to the increase of runoff depth. The different angle of slip surface can affect significantly the stability of residual soil slope. Otherwise, the FOS increases linearly with the increase of friction angle and cohesion of soil for an assumed runoff depth varying from 0 to 0.3 m. The greater the runoff depth, the lower the FOS of the slope.

In conclusion, the runoff depth can significantly control the FOS of the residual soil slope and cause slope failures. The results of sensitivity analysis highlight the significance for considering the drag force due to surface runoff when calculating the FOS of the residual soil slope. The FOS obtained from the modified approach is more reasonable, and this modified approach also can be adopted for evaluating or predicting rainfall-induced slope instability in residual soils.

Disclosure statement

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