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Combining soil macropore flow with formation mechanism to the development of shallow landslide warning threshold in South China

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Because of the physical character of soil from granite weathering and the typhoon rains in South China, the model for early warnings of existing shallow landslides cannot be well applied in that area. This study developed a new shallow landslide model based on the effect of soil macropores for determining the rainfall threshold to post an early warning of the possibility of a shallow landslide in South China. We studied the hydrological effects of macropore flow and proposed a mechanistic model of the formation of shallow landslides by introducing the macropore coefficient of granite residual soil. The rainfall threshold of each slope unit was calculated by combining the hydrological model with the proposed shallow landslide model. Lastly, we tested the calculated result in the Maguihe watershed, Guangdong province, South China, which experienced a group of massive shallow landslides on 21 September 2010. The study results showed that the macropores of vegetation roots had a significant effect by increasing the permeability of granite residual soil. Coniferous forest land has the highest initial infiltration rate and stable infiltration rate, followed by shrub forest land, and then bare land. Statistical verification showed that the accurate prediction rate of the proposed model was 80.65%, which is adequate for early warning of shallow landslides in South China. We discuss the application conditions and parameter calibrations of the proposed model, and offer recommendations for future research.

KEYWORDS

shallow landslide, formation mechanism, soil macropore flow, rainfall threshold, granites weathering crust

Introduction

Shallow landslides induced by heavy rainfall are common phenomena around the world and are frequently accompanied by serious loss of life and property, particularly in mountainous and hilly areas (Asch et al., 2007; Beville et al., 2010; Chien et al., 2015; Palladino et al., 2018; Liu X. et al., 2022; Liu Z. J. et al., 2022). South China is located in a strong monsoon interaction zone. Under the influence of global climate change and intensifying human activities, landslide disasters have been increasing in frequency and people's lives and property in hilly and mountainous areas are facing huge threats (Dai et al., 1999; Gong, 2014; Gong et al., 2021; Shou and Chen, 2021). For example, on 21 September 2010, typhoon Fanapi caused a heavy rainstorm with a single-day rainfall of 814 mm. These conditions resulted in more than 2,000 shallow landslides in Gaozhou City, Guangdong Province, causing 73 deaths and direct economic losses of about 2.2 billion yuan (Wang and Xia, 2012). On 10 June 2019, thousands of shallow landslides occurred in Longchuan County, Heyuan City, Guangdong Province, causing the evacuation of 19,769 people and a direct economic loss exceeding 200 million yuan (Sohu news, 2019). History reminds us that engineering measures cannot always protect us against the forces of nature. Thus, an effective warning system based on well-calibrated rainfall readings is extremely important to mitigate the risks associated with shallow landslides caused by rainstorm in South China.

Currently, the commonly used approaches for analyzing shallow landslides are statistical or physical methods (Adams and Sidle, 1987; Kim et al., 2016; Palladino et al., 2018; Ran et al., 2018; Vandromme et al., 2020; Loche et al., 2022). The statistical method cannot address the physical mechanism or dynamic behavior of landslides and factors such as soil cohesion and friction angle have little correlation with landslide occurrence. The premise of this method for early warning of shallow landslides is to have long-term, relatively complete rainfall data (Florence et al., 2018; Bhardwaj et al., 2019; Gao et al., 2019; Hawas et al., 2019; Juliev et al., 2019; Mekonnen et al., 2022). However, in the mountainous and hilly areas of South China, landslide observation sites are scarce, the research foundation is weak, and relatively few historical records are available. Thus, the essential data such as the time of landslide occurrence and the corresponding accumulated rainfall are often lacking. In this case, the margin of error when using statistical methods to generate early warnings is relatively large. At present, most existing landslide warning systems in South China are based on this method, wherein a warning is issued when an observed value reaches a statistical threshold.

Physical and mechanical methods are based on rainfall infiltration, hydrological effects, and soil instability as a function of the slope to determine the rainfall threshold, or an analysis of the critical hydrological threshold of landslides by studying the movement mechanism and runoff process (Romano et al., 1998; Nguyen et al., 2014; Jiang et al., 2017; Liu et al., 2017; Wu et al., 2020; Qiu et al., 2022; Wang et al., 2022; Zhu et al., 2022). This is presently the most effective method for determining the risk of shallow landslides. With this approach, we can clearly describe the migration of precipitation on the surface and its infiltration into the ground, as well as observe and analyze changes in pore water pressure of soils that occur because of precipitation. In addition, specific changes in slope and the corresponding safety factor value can be calculated using the slope stability model (Wang et al., 2014; Fattah et al., 2017; Liang, 2022). Currently, the main physical models used to evaluate shallow landslides associated with rainfall are the Shallow Slope Stability model (SHALSTAB) (Pradhan and Kim, 2016; Kim, et al., 2019; Shou and Chen, 2021), the Stability Index MAPping model (SINMAP) (Michel et al., 2014; Edirisooriya et al., 2018), and the Transient Rainfall Infiltration and Grid-based Regional Slope Stability model (TRIGRS) (Alvioli and Baum, 2016; Marin et al., 2020; He et al., 2021). These physical models are mainly founded on the infinite slope method based on Mohr-Coulomb failure criteria to reveal landslide potential. The plane sliding model is representative of those methods in which it is assumed that slope instability can be extended indefinitely. Safety factors and the possible location of failure at the surface can be obtained using the limit equilibrium method. Therefore, this paper used the physical method to calculate the threshold for warning against shallow landslides induced by heavy rainfall in South China.

Because of the particular type of weathered granite soil in South China, the formation mechanism is quite different from that of the loess landslides in the northwest and the gravel landslides in the southwest. The surface layers of shallow landslides in South China consist mostly of strongly weathered granite and residual slope accumulation layers, with well-developed surface joints and fissures. Heavy rain can scour the pores, gradually enlarging them to form channels for surface infiltration, turning the precipitation into a preferential flow through large pores. A temporary groundwater level is formed in the loose layer with a larger hydraulic conductivity that causes floating drag and scouring of the rock and soil mass, and eventually leads to the large-scale occurrence of shallow landslides (Dai et al., 1999; Letto and Cella, 2016; Gong et al., 2017; Chen et al., 2022; Liao et al., 2022; Silva et al., 2022). At present, most relevant physical models assume that under conditions of no surface runoff, the mechanism of how macropore flow influences shallow landslides is still unclear. Most research has focused on conducting laboratory tests on soil macropore flow (Ilek et al., 2019; Muddle and Briggs, 2019; Kotlar et al., 2020; Tao et al., 2020; Jarvis and Larsbo, 2022); related studies evaluating the effect of macropore flow on shallow landslide stability are relatively rare, and no relevant physical model incorporating the soil macropore coefficient has been established so far.

Therefore, the overall objective of this study was to develop an innovative model of the mechanism of shallow landslides that takes into account the effect of soil macropore flow. We also

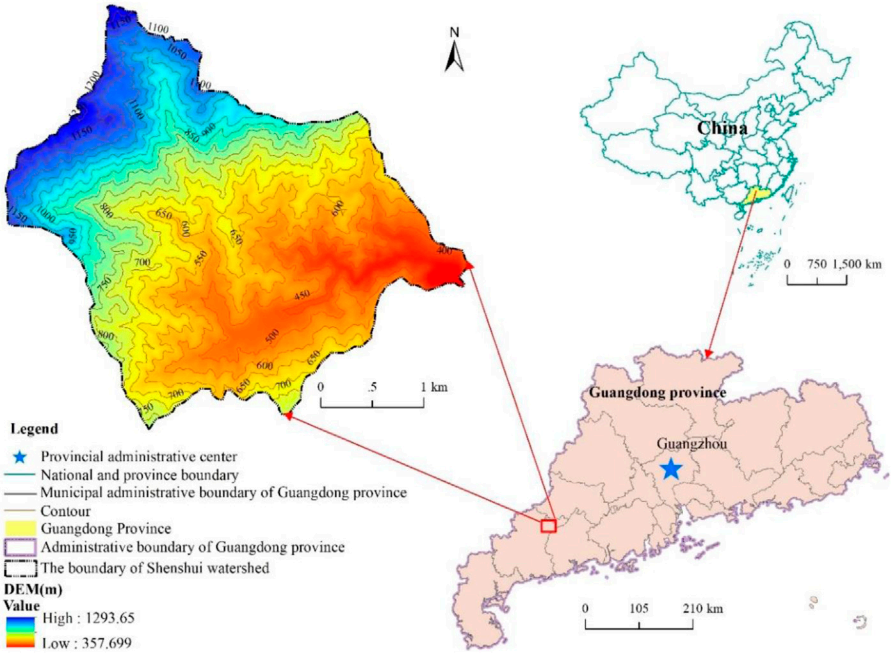

FIGURE 1
Location of the study area.

propose a method for determining the rainfall threshold for generating early warnings of shallow landslides in South China by combining the proposed physical model and the hydrological model. The specific objectives were 1) to analyze the effect of root macropores on soil permeability by field experiments using double-ring infiltration meters, 2) to develop a mechanistic model of shallow landslides including the effect of macropores, 3) to propose a method for determining the rainfall threshold for early warnings of shallow landslides based on the proposed model, and 4) to test the performance of the proposed method based on historical disaster data and from actual field data. To achieve these objectives, the Shenshui watershed, located in western Guangdong Province, South China, was selected as the study area. Because of the complex interaction of natural and artificial factors, this area has suffered repeatedly from shallow landslides from 2010 to 2021, causing serious loss of life and property. The study results provide a scientifically reliable theoretical basis for the mitigation of shallow landslides in South China.

Materials and methods

Study area

The Shenshui watershed, located in Magui town, Maoming City, Guangong Province, South China, was selected as the study area (Figure 1). The watershed area is approximately 9.52 km^2 with a maximum elevation of approximately 836 m, and the length of the main channel is nearly 4.71 km. The river bed gradient is relatively large, ranging from 0° to 58.34°. The range of a typical channel slope, accounting for 39.51% of the study area, is between 30° and 40°. The characteristic parameters of the debris flow gully watershed are listed in Table 1.

The study area is a subtropical monsoon region, with a climate strongly influenced by the South China Sea. The average annual temperature ranges from 21.3°C to 23.2°C (Wang and Xia, 2012). The average annual rainfall is 2160 mm, the maximum average annual rainfall is 3150 mm, and the maximum annual rainfall is 3175 mm as recorded by the Magui hydrological observation station (Liu 2011). Lithologically, the main exposed strata are mainly Late Proterozoic gneissic fine-grained and medium-grained monzonitic granite, Sinian feldspar quartz sandstone mixed with silty slate and phyllite, Jurassic metamorphic rock formations, and Quaternary clay silt and sandy gravel sandwiched in clay siltstone. The parent material of the natural soil is mainly granite, with gneiss and its weathered elements. The study area is subject to heavy rains from typhoons and other severe convective weather. Because of its peculiar natural and geographical conditions, the heavy rains frequently lead to collapses, shallow landslides, debris flows and other disasters. For example, on 21 September 2010, Magui town suffered from many collapses, landslides, and debris flows because of typhoon Fanapi (Figure 2), resulting

TABLE 1 Morphological characteristics of the study area.

Morphological factors	Value
Area (km^2)	9.52
Maximum altitude (m a.s.l.)	1293.65
Minimum altitude (m a.s.l.)	357.70
Elevation difference (m)	835.95
Main river channel length (km)	4.71
Average channel slope (°)	28.45
Range	23°26′53″–23°29′9″ N; 110°7′35″–110°10′17″ E

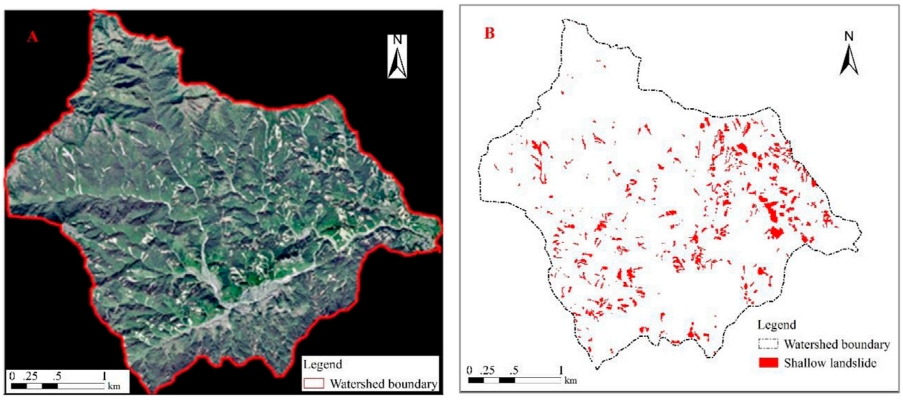

FIGURE 2
Distribution of shallow landslides in the Shenshui watershed induced by typhoon Fanapi. **(A)** Remote-sensing images after the event and **(B)** distribution of shallow landslides.

in the deaths of at least 73 people and damage to 8300 houses costing 2.2 billion yuan in economic losses (Wang and Xia, 2012), and having a serious impact on the environment and the lives of local residents. The shallow landslides occurred mostly at the top of the hill and halfway up the mountain, where loose solid materials were abundant. We determined the occurrence of shallow landslides induced by this event from the remote-sensing image data of the study area (Figure 2). It can be seen that the area of shallow landslides was nearly 0.60 km^2; therefore, the early warning of the risk of shallow landslides in this area was extremely important.

Field testing of effects of macropore flow on permeability enhancement

Numerous mass disaster events in South China, such as the Magui disaster on 21 September 2010 and the Longchuan disaster on 10 June 2019, show that mass shallow landslides are mainly concentrated on the mountains with well-developed vegetation. However, shallow landslides rarely occur in mountains with poor vegetation development. This is because the macropores of vegetation roots have a significant effect on increasing the permeability of granite residual soil. To discuss the effect of root macropores to the permeability of granite residual soil in South China, we measured the infiltration properties of granite residual soils under representative vegetation in South China using the double-loop method. Three cover types are used: coniferous forest, shrub forest and bare land. Every cover type conducted three groups of field tests. The field test of double-loop method was carried out according to the relevant specifications, mainly measuring the initial infiltration rate and stable infiltration rate of granite residual soils.

Mechanistic model of shallow landslides and the effect of macropores

According to the rainstorm infiltration mechanism of landslide formation, the surface runoff is taken as the node with two conditions being considered. With little surface runoff of rain, the groundwater infiltration and slope stability coefficient are controlled by the amount of rainfall. In the second case, with surface runoff, the volume of groundwater infiltration depends on the presence of large soil pores, which causes the soil to become saturated; thus, rainfall infiltration is mainly affected by the hydraulic conductivity of the saturated soil. It is assumed that the landslide body is relatively impermeable, a temporarily confined aquifer is located below the slip surface, and groundwater flows and circulates in deep layers along the confined aquifer. In South China, the shallow landslides are mainly induced under the second case. Thus, this study focused on landslide stability under the condition of surface runoff during a heavy rainstorm.

Under the action of rain, the flotation force F_b acting on the landslide surface generated by the macropore flow is a non-negligible factor for rainstorm-induced landslides. The formula for calculation of F_b can be express as:

$$F_b = \rho_w g Z_w L \cos\theta \tag{1}$$

where F_b is the flotation force (N), ρ_w is the water density (kg/m^3), g is the gravitational acceleration (9.81 N/kg), Z_w is the depth of the aquifer from the surface (m), L is landslide surface length (m), and θ is the terrain gradient (°).

Innovatively considering the influence of macropore flow on landslide formation, the macropore coefficient (λ) is introduced here. The hydrostatic pressure F_t generated by the macropores is:

$$F_t = \lambda \rho_w g Z L \cos^2\theta \tag{2}$$

where F_t is the hydrostatic pressure generated by the macropores (N), λ is the macropore coefficient of the soil (%), and Z is the soil thickness (m).

When the seismic force is ignored and surface runoff occurs, the slope stability coefficient F_s can be obtained by considering the sliding body gravity, hydrostatic pressure, seepage pressure and floating force after formation of the temporary groundwater level:

$$F_s = \frac{CL + \left(\rho_s g Z L\cos^2\theta - \lambda\rho_w g Z_w L\cos^2\theta - \rho_w g Z_w L\cos\theta\right)\tan\varphi}{\rho_s g Z L\cos\theta\sin\theta + \rho_w g Z_w L\cos\theta\sin\theta} \tag{3}$$

where F_s is the slope stability coefficient, C is the cohesion of the soil (kPa), ρ_s is the density of soil (kg/m^3), and φ is the internal friction angle (°) of the soil.

Divide both the numerator and denominator of the above equation by $\rho_s g Z L$, as:

$$F_s = \frac{\frac{C}{\rho_s g Z} + \left(\cos^2\theta - \lambda\frac{\rho_w}{\rho_s}\frac{Z_w}{Z}\cos^2\theta - \frac{\rho_w}{\rho_s}\frac{Z_w}{Z}\cos\theta\right)\tan\varphi}{\cos\theta\sin\theta + \frac{\rho_w}{\rho_s}\frac{Z_w}{Z}\cos\theta\sin\theta} \tag{4}$$

Let $\gamma = \frac{\rho_w}{\rho_s}$ represent the density ratio of water to soil in the landslide area (dimensionless), and let $w = \frac{Z_w}{Z}$ be the saturation state of the slope soil, which is the saturation factor. The above formula can be further simplified as:

$$F_S = \frac{\frac{C}{Z\gamma_s} + \left(\cos^2\theta - \lambda\gamma w\cos^2\theta - \gamma w\cos\theta\right)\tan\varphi}{\cos\theta\sin\theta + \gamma w\cos\theta\sin\theta} = \frac{\frac{C}{Z\gamma_s} + \left(1 - \lambda\gamma w - \gamma w\frac{1}{\cos\theta}\right)\cos^2\theta\tan\varphi}{(1+\gamma w)\cos\theta\sin\theta} \tag{5}$$

Divide both the numerator and denominator of the above equation by $cos^2\theta$, and let $C' = \frac{C}{\rho_s g Z cos^2\theta}$ represent the effective soil cohesion, which is a variable associated with the soil cohesion (C). The above formula then becomes:

$$F_s = \frac{C' + \left(1 - \lambda\gamma w - \frac{\gamma w}{\cos\theta}\right)\tan\varphi}{(1+\gamma w)\tan\theta} \tag{6}$$

where w is the saturation state of the slope soil (dimensionless), which can be calculated by the following formula:

$$w = \frac{qa}{T\sin\theta} \tag{7}$$

where q is the effective rainfall (mm), a is the ratio of the rain collection area (the catchment area) to the drainage width (m), and T is the transmissibility ($T = KZ\cos\theta$, m^2/d), where K is the permeability coefficient (m/d or cm/s), and Z is the soil thickness (m). The F_s can be given as:

$$F_s = \frac{C' + \left(1 - \lambda\gamma\frac{qa}{T\sin\theta} - \frac{\gamma qa}{T\sin\theta\cos\theta}\right)\tan\varphi}{\left(1 + \gamma\frac{qa}{T\sin\theta}\right)\tan\theta} \tag{8}$$

Rainfall threshold of shallow landslides

When F_s >1, the slope is stable; when F_s =1, the slope is in a state of limit equilibrium; and when F_s <1, the slope is unstable. Considering the slope is in a state of limit equilibrium (F_s =1), Eq. 8 can further be simplified as:

$$q = \frac{T\sin\theta\left(C' + \tan\varphi - \tan\theta\right)}{a\gamma\left(\lambda\tan\varphi + \tan\theta + \tan\varphi/\cos\theta\right)} \tag{9}$$

The main reason for shallow landslides during heavy rainfall in South China is the rise in groundwater level, soil saturation and the reduction in effective shear strength caused by continuous heavy rainfall. The limit equilibrium theory can well express the coupling relationship between hydrology and geology. Therefore, according to the runoff characteristics and mechanical limit equilibrium of slopes in small watersheds, an early warning threshold model of shallow landslides occurring in groups can be established based on the hydrological-mechanical mechanism. The hydrological model of this study used the improved SCS model to simulate the relationship between rainfall and infiltration, and the established slope limit equilibrium formula to analyze the stability of the slope under heavy rainfall. The calculation unit used in this study is the slope unit. The small watershed digital elevation model (DEM) is used to realize the automatic

TABLE 2 Comparison of infiltration performance of three different vegetation coverage types.

The cover type	Initial infiltration rate (mm/min)			Stable infiltration rate (mm/min)		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
Coniferous forest	36.24	35.05	34.87	6.38	5.70	5.62
Shrub forest	22.82	22.75	25.02	2.91	3.08	3.05
Bare land	15.49	16.13	14.77	1.67	1.81	1.81

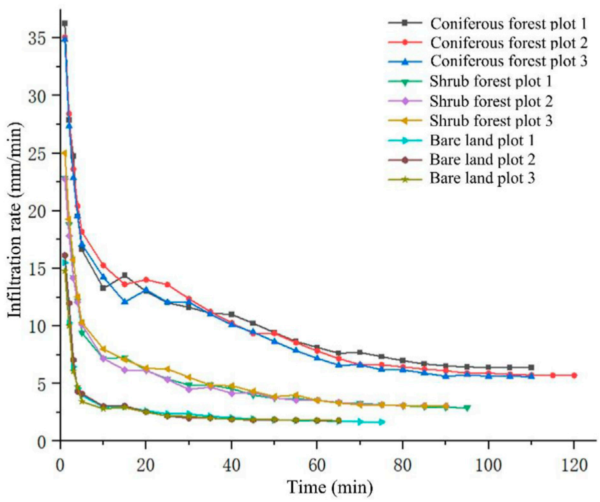

FIGURE 3
Infiltration process of different vegetation coverage in granite residual soil in South China.

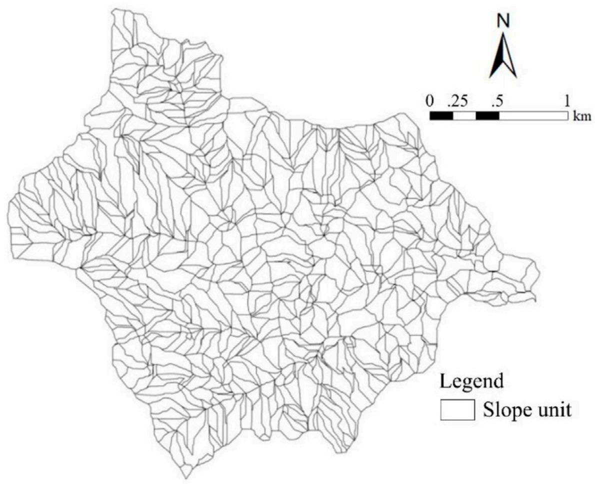

FIGURE 4
Divisions of the slope unit in the study area.

division of the slope unit, and each unit is coded and given element attribute information. On this basis, GIS spatial analysis is used to calculate the warning threshold of each division unit.

Results and discussion

Field test of the double-loop method

The test result of the initial infiltration rate and stable infiltration rate of granite residual soils in the three cover types are shown in Table 2. The processes of soil infiltration on different vegetation plots are shown in Figure 3.

It can be seen that although there are differences in the specific infiltration process on the different vegetation plots, the overall trend is the same. The soil infiltration rate was high in the initial stage, and decreased rapidly over a short period of time; then, the rate of decrease of infiltration slowed down, and the final infiltration rate approached a stable value.

In this paper, two infiltration indicators, initial infiltration rate and stable infiltration rate, were selected to analyze and evaluate the granite residual soil permeability in each plot (Table 2). It can be seen that the initial infiltration rate and the stable infiltration rate of coniferous forest land were the highest, followed by shrub forest land, and bare land. This is because the decomposing leaves form humus, and soil under the action of humus forms aggregates with a large pore structure. In addition, the coniferous forest soil is more transparent with many developed roots, root-soil gaps, rotted root channels and other large pores. The macropores of vegetation roots have a significant effect on increasing the permeability of granite residual soil. Therefore, a determination of the stability of a slope covered by vegetation must take into account the effect of macropore flow, which strongly influences slope stability; otherwise, the prediction of shallow landslides will be very different from the actual situation.

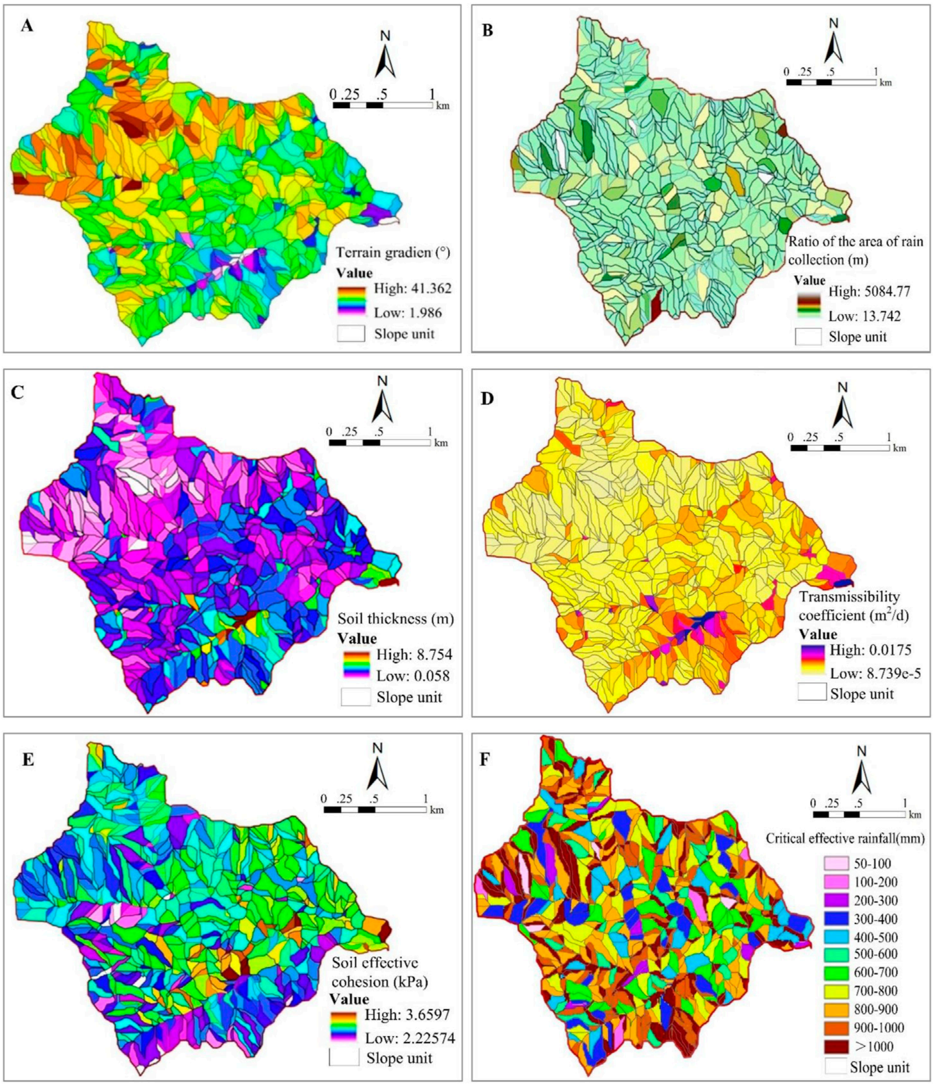

FIGURE 5
Calculated results of proposed model parameters and the critical effective rainfall of each slope unit in the study area. **(A)** Terrain gradient; **(B)** ratio of the area of rain collection; **(C)** soil thickness; **(D)** soil transmissibility coefficient; **(E)** soil effective cohesion; and **(F)** critical effect rainfall.

Calculated result of rainfall threshold of shallow landslides

Division of early warning unit

On the ArcGIS 10.5 platform, according to the digital elevation model (DEM) of the study area, the source-cutting method was adopted, and the ridge line and the valley line were used as the boundaries. The slope unit in the study area was divided into 624 slope subunits (Figure 4).

Results of model parameter calculations

In our proposed physical model of shallow landslides, the main parameters were terrain gradient (θ), the ratio of the area of rain collection (a), the soil transmissibility coefficient (T), the soil thickness (Z), the soil internal friction angle (φ), the soil effective cohesion (C'), the density ratio of water to soil in landslide (γ), and the soil macropore coefficient (λ).

1) Terrain gradient of the slope unit (θ)

Slope is the most influential element in the determination of the risk factor for shallow landslides. Using GIS software, we first calculated the slope of each grid, and then used the spatial statistics function to count the average slope of each slope unit. The result is shown in Figure 5A.

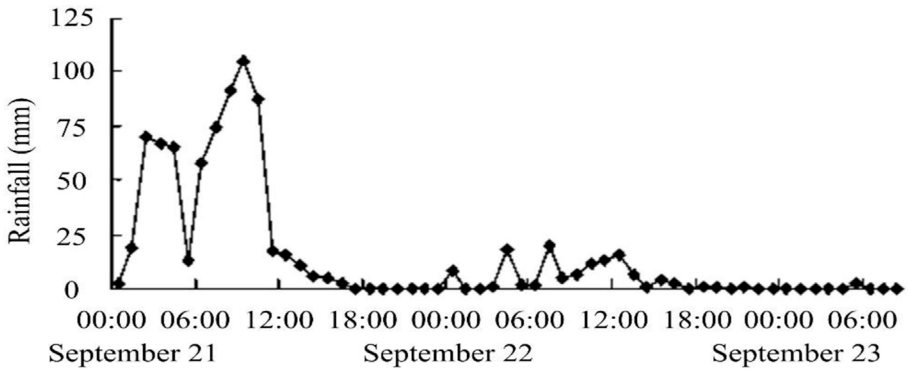

FIGURE 6
Precipitation levels associated with the landslide event of 21 September 2010.

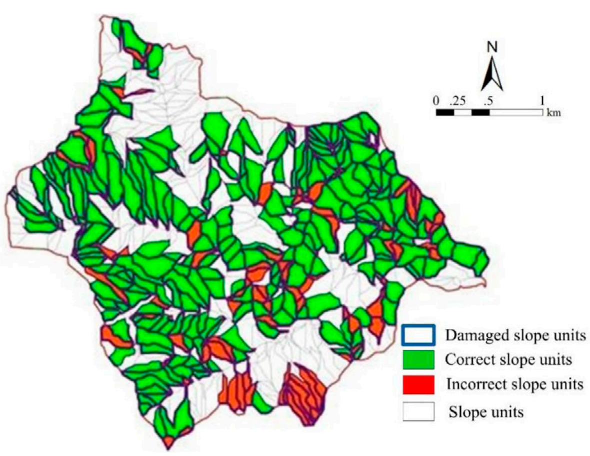

FIGURE 7
Comparison between the calculated results from the landslide early warning model and the actual occurrence.

2) The ratio of the area of rain collection (a)

The ratio of the area of rain collection was calculated as:

$$a = \frac{A}{b} \tag{10}$$

in which a is the ratio of the area of rain collection (m), A is the catchment area above the unit slope (m^2), which can be directly calculated in GIS software through the area operation function. B is the drainage width (m), which can be calculated in the GIS software by length. The results of calculating the ratios of the areas of rain collection are shown in Figure 5B.

3) The soil thickness (Z)

Soil thickness is one of the important factors affecting shallow landslides. In this study, in order to obtain the distribution of soil thickness in study area, field measurements of soil depth were made. The main measurements were soil thickness and surface slope. The measurement position of soil layer thickness was selected in the exposed section area, which was performed manually using an auger and tape measure. Based on the results of field measurements, a regression analysis was carried out on the relationship between slope and soil layer thickness, as:

$$Z = -2.864 \ln(\theta) + 10.719 \tag{11}$$

where Z is the soil thickness (m) and θ is the soil surface slope (°). Through DEM analysis, the average slope (θ) of each slope unit was obtained; then, the soil thickness (Z) was calculated by Eq. 11 (Figure 5C).

4) The soil transmissibility coefficient (T)

The soil transmissibility coefficient was calculated by the following equation:

$$T = KZ\cos\theta \tag{12}$$

where T is the soil transmissibility coefficient (m^2/d), K is the soil permeability coefficient (m/d or cm/s), Z is the soil thickness (m), and θ is the terrain gradient of the slope unit (°). The distribution of soil transmissibility coefficient is shown in Figure 5D.

5) The soil effective cohesion (C')

A slope is a unified system composed of its upper soil layer and covered vegetation, and the effective cohesion of the soil is the combination of soil cohesion and plant root cohesion. In this

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TABLE 3 Method of obtaining the key parameters of the proposed physical model of shallow landslides.

Categories	Parameters	Parameters obtaining methods						
		Data collection	Investigation	Field observation	Remote sensing interpretation	Experimental analysis	Computational simulation	Weather forecast
Topographic parameter	Terrain gradient (θ)	●	●				●	
	Ratio of the area of rain collection (a)	●	●				●	
Geological parameter	Internal friction angle(φ)	●	●	●		●	●	
	Cohesion (C)	●	●	●		●	●	
	Soil thickness (Z)	●	●	●		●	●	
	Transmissibility coefficient (T)	●	●	●		●	●	
	density ratio of water to soil in landslide (dimensionless)	●	●	●		●		
	Soil macropore coefficient (λ)	●	●	●		●		
Vegetation parameter	Vegetation cover index ($NDVI$)	●	●		●		●	
Hydrological parameter	Preliminary soil moisture (AMC)	●	●	●	●		●	●
	SCS curve parameters (CN)	●	●	●	●		●	●
	Retention parameter (S)	●	●	●	●		●	●
	Initial infiltration (Ia)	●	●	●	●		●	●
Meteorological data	Precipitation (P)	●	●	●	●	●	●	●

study, the effective cohesion of the soil as related to vegetation coverage was calculated by the following formula:

$$C' = C_{max} \frac{NDVI(x, y) + 1}{2} \tag{13}$$

where C_{max} is the maximum value of soil cohesion (kPa), which was obtained through literature review and field surveys, $NDVI(x, y)$ is the vegetation cover index, which can be extracted from remote sensing images by the ENVI software. The calculated result of soil effective cohesion is shown in Figure 5E.

6) The density ratio of water to soil (γ) and the soil macropore coefficient (λ)

The density ratio of water to soil (γ) in the landslide area was a fixed value equal to the ratio of the density of water to the density of soil (dimensionless). In this study, the density ratio of water to soil was 0.378.

The soil macropore coefficient (λ) was obtained by field experiments on the soil (dimensionless). In this study, the soil macropore coefficient of the slope unit was between 0 and 0.04, with an average value of 0.025.

Lastly, according to Eq. 9 and the algebraic calculation of each factor in ArcGIS software, the critical effective rainfall amount triggering shallow landslides in each slope unit can be obtained (Figure 5F).

It can be seen that the terrain slope of the slope unit in the study area varied from 1.986° to 41.362°. The upstream slope of the small watershed was larger, and the slope of the valley and downstream areas was relatively gentle (Figure 5A). The ratio of the area of rain collection in the study area ranged from 13.742 to 5084.77 (Figure 5B). The thickness of granite residual soil in the Shenshui watershed was relative high, with a maximum value of 8.754 m (Figure 5C). The transmissibility coefficient was between 0.00008739 m^2/d and 0.0175 m^2/d (Figure 5D). The soil effective cohesion was relatively small, with a maximum value of 3.6597 kPa (Figure 5E). It can be seen that when the effective rainfall was greater than 50 mm, some slope units slided (Figure 5F). The greater the effective rainfall, the greater the number of unstable slope units and the larger the group of landslides occurring. We compared the actual measured rainfall with the critical rainfall, and obtained the unstable state of the slope unit under the actual rainfall, so as to carry out early warning and forecasting for each slope.

Verification of proposed model

On 21 September 2010, the residents of Magui town experienced many shallow landslides due to the strong rains associated with typhoon Fanapi. The total rainfall reached 829.7 mm (from 19 September, at 20:00 h, to 23 September, at 20:00 h). The time of heavy precipitation in Magui Town on 21 September occurred from 00:00 to 12:00, with two peaks of very heavy precipitation. One peak occurred at about 02:00 h and the precipitation was 74 mm/h. The other peak was at 11:00 h, and the peak precipitation reached 105.5 mm/h. The rainfall process of this event is shown in Figure 6.

By inputting the above precipitation process data into the improved hydrological SCS model, we were able to obtain the actual effective rainfall threshold triggering shallow landslides on each slope unit. Then, by comparison with the critical effective rainfall calculated by the physical model proposed in this study, the spatial distribution of unstable slope units calculated by the proposed theoretical model can be illustrated (Figure 7).

Figure 7 shows that within the scope of the disaster, there were 336 slope units on which shallow landslides occurred. According to the results of the proposed model calculations, landslides happened on 271 slope units, and the accuracy of the prediction rate was 80.65%. Thus, the model proposed in this study was successfully used for early warning of shallow landslides in the Magui River Basin.

Discussion

The key parameters of the proposed physical model for early warning of shallow landslides can be roughly divided into five categories, namely topographic parameters, geological parameters, hydrological parameters, vegetation cover parameters, and meteorological parameters. The key parameters and the methods for obtaining them are shown in Table 3.

The above model parameters are very important for the calculation of shallow landslide warning thresholds. Therefore, in specific applications, it is necessary to test and calibrate these parameters, to ensure that they are in agreement with the actual results, and only in that way can the predicted warning threshold be accurate. The proposed model can be used in those areas with soil composed of weathered granites and subject to typhoon rainstorms, such as South China. In the future, we will continue to test this model on other watersheds where shallow landslides have occurred, so as to increase its accuracy for use in other regions.

Conclusion

In this study, we developed a physical model of shallow landslides, influenced by the effect of soil macropore flow, and proposed a method for determining the rainfall threshold for early warnings of shallow landslides based on the hydrological model and the proposed physical model in South China. The conclusions are:

1) We measured the infiltration properties of granite residual soils under three representative vegetation covers in South China using the double-loop method. The initial infiltration

rate and the stable infiltration rate of coniferous forest land were highest, followed by shrub forest land, and bare land. The macropores of vegetation roots had a significant effect on increasing the permeability of granite residual soil; therefore, the type of vegetation coverage and the infiltration effect of macropores must be considered in determining the stability of a developed slope, otherwise the prediction of shallow landslides will be very different from the actual situation.

2) Considering the effect of macropore flow on shallow landslides, we introduced the macropore coefficient of soil into the shallow landslide mechanism model, and established a revised shallow landslide physical model of granite residual soil in South China.
3) We applied the proposed physical model to calculate the rainfall threshold for early warning of shallow landslides. The massive number of shallow landslides induced by the heavy rainfall on 21 September 2010 was used to verify the calculated results, and revealed a prediction accuracy of 80.65%. Thus, the model proposed in this study provided useful early warnings of the shallow landslides in the Magui River Basin.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JW carried out the field investigation, data analysis, and manuscript writing. QG involved in manuscript supervision. SY undertook the field survey, participated in the discussion and decision-making process. JC was involved in writing reviewing, manuscript editing, and supervision. All the authors participated and contributed to the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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