Research Article

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Soil Disintegration Characteristics of Collapsed Walls and Influencing Factors in Southern China

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Abstract: Collapsed walls cause collapsed mounds, and the disintegration characteristics of collapsed walls are thus closely linked with the occurrence of collapsed mounds. The current study examines the disintegration characteristics and the physical and chemical properties of collapsed walls. A multilevel analysis was conducted by obtaining soil samples from four layers of a collapsed wall. The results showed that 1) the physical and chemical properties of the soil samples (red soil layer, sandy soil layer, debris layer, gravel and eluvial breccia) are closely related to the weathering degree of the crust; 2) gravel and eluvial breccia disintegrated in the shortest time, whereas red soil exhibited the slowest disintegration in the vertical section of the collapsed wall. The order of the disintegrating ratio of the layers is as follows: red soil layer < sandy soil layer < debris layer < gravel and eluvial breccia. Initial water content significantly influenced the disintegration ratio of the red soil layer and sandy soil layer, whereas its effect on the debris layer and gravel eluvial breccia is minimal; and 3) most of the physical and chemical properties of the collapsed wall are significantly correlated with the disintegration ratio of the soil sample. The following physical and chemical properties, which are positively correlated with the disintegration ratio, are arranged based on highest to lowest correlation coefficient: sand content, MgO, natural water content, K₂O, CaO, exchangeable sodium, pH, porosity, Na₂O, and cation exchange capacity. The following physical and chemical properties, which are negatively correlated with the disintegration ratio, are organized based on highest to lowest correlation coefficient: cosmid, Fe₂O₃, silt particle, Al₂O₃, TiO₂, SiO₂, organic matter, free iron oxide, and free alumina. Only exchangeable calcium, saturated water content, specific gravity of soil particles, and dry density of soil particles are significantly correlated with the disintegration ratio. The correlation coefficient indicates that the disintegration ratio

and soil structure, as well as the chemical content of clay minerals, are closely correlated. The study helps explain the mechanism of wall collapse and provides references for developing protective measures against erosion.

Keywords: Benggang erosion, collapsed wall, disintegration characteristics, granite red soil region in southern China

1 Introduction

In the granite areas of tropical and subtropical South China, there is a widely distributed erosional phenomenon with associated small-scale erosional landforms called “Benggang erosion” (Figure 1) by the local people [1]. This Benggang erosion is a specific form of soil erosion in the granite red soil region of southern China. Benggang can be defined as an erosional landform with a very high rate of sediment transfer, which is formed on hill slopes with a covering of thick granite weathering mantle and caused by the joint operation of mass wasting and flowing water erosion, with the former being dominant [1, 2]. Benggang erosion is one of the most important indications of serious soil erosion. Although the area of Benggang erosion is limited, these eroded soils cause more serious damage to the natural environment and more adversely affect socio-economic development than other types of soil erosion [1, 3].

Studies on the mechanism of Benggang erosion have been conducted to determine ways to control this type of erosion. Scholars have analysed the influence of geomorphology, geological foundation, vegetation, groundwater activity, slope hydrology, slope, and climate on collapse and erosion [1, 3–6]. However, the mechanism of Benggang erosion remains unclear. Collapsed walls form a major part of Benggang erosion, which is an almost vertical ledge that is produced by the dumping and sliding of the weathering crust under the action of gravity and water. Collapsed walls are usually between a few metres to 10 metres high. Collapsed walls facilitate soil disintegration caused by gravity, thereby resulting in colluvial heaps. Col-

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Figure 1: A view of a typical Benggang erosion in Deqing county of Guangdong province China.

lapsed mounds are eroded because of the disintegration of collapsed walls. These mounds do not form or develop without the disintegration of collapsed walls. The disintegration of collapsed walls is the most crucial aspect of the formation of Benggang erosion, and this process produces materials that facilitate the movement of collapsed mounds [7]. Scholars have determined that collapsed walls play a crucial role in the formation of Benggang erosion [7–10]. However, research on the collapsing mechanism of the collapsed wall soil is still in the exploratory stage. The collapse of the collapsed wall soil will inevitably involve the participation of water, and the collapsed wall soil will disintegrate when it encounters water. Therefore, to study the collapse of collapsed wall soils, we must first study its disintegration characteristics. Due to the deep collapse of the weathering crust of South China granite, its layering is particularly obvious, and its disintegration characteristics should be different. This study will evaluate the disintegration characteristics and influencing factors of different levels of collapsed soil. Regarding the study of soil disintegration characteristics, scholars have conducted research on several individual aspects, such as the disintegration characteristics of different soil types (such as granite residual soil) on engineering geology and soil mechanics. Jiang Fangshi *et al.* studied the soil corrosion resistance of collapsed bodies, the disintegration test was used to determine the disintegration time of the soil, and it was found that the collapsed soil was more prone to disintegration than other collapsed sites [4]; Yan Bo and Niu Dekui, *et al.* discovered that granite weathered soil can disintegrate under the action of rainwater, causing the soil structure to be destroyed [11, 12]; Liu Danlu *et al.* studied The difference in the soil disintegration rate of the granite pro-

file under different water quantities from the perspective of initial water content [13]. Although the process of soil disintegration has attracted the attention of scholars, the existing research on the disintegration characteristics and their influencing factors at different levels of collapsed soil is still less frequently reported, especially for deeper levels. There is a lack of research on the multi-layer and variable water content-based changes of granite weathering crust collapse and the physicochemical properties of disintegration. In light of this fact, this study collected soil samples from four layers of collapsed soil (red soil layer, sandy soil layer, debris layer, gravel, and eluvial breccia) to analyse their physical and chemical properties and used a homemade disintegrator to test the amount of disintegration of the layered soil under different levels of water content. Correlation analysis was used to show that the physical and chemical factors were closely related to the disintegration amount and illustrated the disintegration characteristics of the collapsed soil and its influencing factors. The study helps explain the mechanism of wall collapse and provides references for developing protective measures against erosion.

2 Materials and methods

2.1 Study area

This study area is located in the town of Maxu, Deqing County, Guangdong Province. Deqing County (111°31'–112°15'E; 23°04'–23°30') is located in western Guangdong Province, on the northern shores of the Xijiang (west) River. Deqing County is located in the south of the Tropic of Cancer and has a subtropical monsoon climate, an annual average rainfall of 1516.5 mm, an annual average temperature of 21.5°C, and an annual average sunlight quantity of 1848 h. The rocks in the study area are biotite granite porphyry of the Yanshan Period with a weathering crust thickness of 30–60 m. Samples were collected in an active Benggang erosion area, which was one of the 39 Benggang erosion areas in the region.

2.2 Layering and sampling

The crushing degree, decomposition, and leaching of mineral rock and the generation of new minerals in the soil samples were analysed according to the physical–chemical weathering features; analysis was conducted based on a previous study on weathering crust [7]. The

granite laterite weathering crust from the collapsed wall sample was divided into five levels: red soil layer (completely weathered zone), sandy soil layer (strongly weathered zone), debris layer (weakly weathered zone), gravel and eluvial breccia (weakly weathered zone), and bedrock. Soil samples were obtained from the four levels of the collapsed wall (Figure 1), and the samples included loose soil and undisturbed soil. A straight shearing cutting ring ($\Phi 61.8 \times 20$ mm) was used to acquire the undisturbed soil to investigate the effect of moisture content on the soil strength characteristics. Five levels of water change were identified. Twenty cutting ring test pieces were used for each layer of soil. Sampling was conducted four times. One set of samples was used for bulk density and natural water content analysis. The three remaining samples were used for three runs of disintegration tests. Four collapsing wall soil layer locations were used, with 20 samples taken at each site, for a total of eighty samples. Each sample was numbered, wrapped in plastic wrap, and then placed in a crisper. Meanwhile, approximately 1 kilogram of bulk soil was obtained for physicochemical analysis. The shearing cutting ring soil samples that were immediately returned to the room were used to analyse the changes in soil water content in the five groups. The soil samples in Groups 1 and 2 were air-dried for seventy-two and forty-eight hours, respectively, before the experiment began. The soil samples in Group 3 were directly measured after they were not soaked in a container for twenty-four hours. The soil samples in Group 4 were immersed in deionized water for 5 seconds. The surfaces of the soil samples in Group 5 were sprayed with watering cans until water saturation was achieved. The soil moisture content of the five groups was determined using a homemade disintegrating instrument to measure the degree of disintegration under different soil moisture contents and soil levels. The samples were divided into three groups to repeat the measurements, and the average value of the results was determined. The amount of disintegration of the different soil layers of the collapsed wall and the initial soil moisture content in the soil samples were presented in a diagram.

2.3 Test methods

2.3.1 Soil disintegration test

The disintegration characteristics of the samples were determined through observation, buoy methods, and mass methods. The wetting disintegration of the samples was observed by conducting qualitative analysis on the sample, although buoy shaking and water vacuoles attached

to a buoy are widely used in analysing clay samples. The disintegrating process is relatively slow, which lengthened the observation time. Based on the results of previous studies [14, 15], the current study uses the mass method to directly measure the amount of disintegration. Soil quality changes include the quality decrement and mass addition of the soil sample because increased water absorption causes disintegration. The diagram of the disintegration device is shown in Figure 2. The basic assumption is that the density of water remains constant during the disintegration process of the soil samples. The quality of the samples was assessed after disintegration. Testing equipment mainly includes a homemade hob that is approximately $900 \text{ mm} \times 600 \text{ mm} \times 600 \text{ mm}$, a precision electronic balance with a measuring range of 2,000 g and precision of 0.01 g, a glass tank that is approximately $600 \text{ mm} \times 300 \text{ mm} \times 300 \text{ mm}$, a $100 \text{ mm} \times 100 \text{ mm}$ screen with a mesh size of $10 \text{ mm} \times 10 \text{ mm}$, and a hanger. Other test instruments include a stopwatch, camera, and video camera. The test data were displayed on an electronic screen to conveniently obtain accurate results. The amount of disintegration is computed by using the formula derived by Lan Zexin [15].

$$A_t = \frac{m_o - m_t}{m_o - m_e} \times 100 \quad (1)$$

A_t refers to the disruption amount of the sample at time t (%), m_o indicates the reading of the initial static hydraulic balance in water (g), m_t denotes the reading of the balance at corresponding time t (g), and m_e refers to the hydraulic balance reading of the zero load of the wire grid (g).

Figure 2: Schematic of disintegration device.

When operating the disintegration device, the samples were placed in the middle of the screen and quickly transferred to water. The stopwatch was activated, and the balance reading was immediately measured at the beginning. The balance readings were recorded every 30 s after the start of the test, i.e., 30, 60, 90, 120, 150, 180 s until 600 s, and then recorded every 5 min until full disintegra-

tion occurred at the 480 min log balance reading. When the sample completely dropped through the grid, the test ended. Three samples in the moisture content of each level of the collapsed wall were obtained, and the results of the three samples were averaged. During the disintegration test, the disintegration changes in the soil sample and quality changes in the water-absorption process are shown in the electronic balance. The current study uses the readings on the electronic balance at different time periods as quantitative indicators of disintegration characteristics to facilitate data processing. The disintegration value of the granite profile under different initial moisture contents is obtained by employing Formula (1), and the disintegrating line chart under the varying initial moisture contents is established.

2.3.2 Measuring methods for physical and chemical properties of collapsed wall soil

In soil particle analysis, the soil particles with particle diameters > 2 mm will be examined using the sieve analysis method, whereas soil particles with particle diameters ≤ 2 mm will be observed by utilizing an American Microtrac S3500 series laser particle size analyser. Soil moisture, dry density of soil particles, soil porosity, soil clay elements of SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , CaO , MgO , K_2O , Na_2O , soil pH, soil organic matter, cation exchange capacity, exchangeable calcium, free iron oxide, and alumina free exchangeable sodium are tested according the analysis of soil physico-chemical properties [16].

2.4 Correlation analysis

Correlation analysis refers to the analysis of two or more relevant variable elements to measure their relative similarities. The correlation between two variables can be measured by using many statistical values, and the most commonly used is the Pearson correlation coefficient. The calculation formula is:

$$R = \frac{1}{n-1} \sum_{i=1}^n \left(\frac{X_i - \bar{X}}{s_X} \right) \left(\frac{Y_i - \bar{Y}}{s_Y} \right) \quad (2)$$

where R is the Pearson correlation coefficient; n is the number of samples; and X_i and Y_i are the values of X and Y , respectively, for the i -th sample; $\bar{X}$ and $\bar{Y}$ are sample mean values of X and Y , respectively; s_X are the sample standard deviations of X ; s_Y represent the sample standard deviations of Y . To identify the physical and chemical properties that influence the disintegration characteristics of a

collapsed wall in its natural state, the study adopted the physicochemical properties of the four layers of the collapsing wall soil (X), and determined the amount of disintegration under natural water content after 1, 2, 5, and 10 minutes (Y) under the condition of natural water content and calculated Pearson correlation coefficients using Excel 2003. Each physicochemical property and the amount of disintegration under natural water content after 1, 2, 5, and 10 minutes had three repetitions. $n = 12$ when $p = 0.01$ and $R = 0.66$. A significant correlation test was performed to identify the physicochemical factors that had significant correlations with the amount of disintegration under natural water content after 1, 2, 5, and 10 minutes.

3 Results

3.1 Qualitative observation of collapsed wall of granite weathering crust in study area

The typical red clay type granite weathering crust in the study area can be categorized based on five features [7, 8], namely, the mineral composition of each layer, the degree of weathering, soil structure, grain size, and colour. The difference in the samples in terms of these characteristics results in varying resistance to impact, erosion, collapse, and sliding. The soil of the collapsed wall in the study area was divided into a red soil layer (completely weathered zone), sandy soil layer (strongly weathered zone), debris layer (weakly weathered zone), gravel and eluvial breccia layer (weakly weathered zone), and bedrock based on a previous study [7, 8]. The granite weathering crust underwent a unique chemical weathering process. The weathering degree of each element and the generation of new minerals from the surface to the bedrock vary and occur gradually. The characteristics of the weathered zone of the collapsed wall are as follows:

The red soil layer (completely weathered zone) has a thickness of approximately 1–3 m. This palm-red layer is located at the top of the weathering crust and is mostly composed of minerals that are kaolinized completely and enriched with iron and aluminium. The strong oxygenation and intensive weathering resulted in an unrecognizable structure that is composed of soft clay and residual quartz grains. The majority of silicon oxide, calcium, magnesium, potassium, and sodium were leached, drained away and exhibited clay moisture expansion and xerochasy [5]. The soil underwent an acidic reaction.

The sandy soil layer (strongly weathered zone) has a thickness of approximately 3–35 m and is located in the

central part of the weathering crust. This layer is very deep, and most are light red. Feldspar is kaolinized. Strong weathering occurred, and the native crystal structure is clear to the naked eye. The crystal is loose and easily crushed to powder. The components of this layer have high iron oxide content, and weathering fractures occur between layers. Soil texture is heavy and exhibit characteristics of moisture expansion and xerochasy. The soil has an acidic reaction.

The debris layer (weakly weathered zone) belongs to the lower part of the primarily kaolinite eluvial belt. This layer is orange and has a thickness of approximately 10 to 20 metres. Feldspar was weathered as kaolin. The original rock crystal structure of this layer was well preserved, and it is fragile and breaks up with hand pressure. This layer belongs to the weathered zone.

The gravel and breccia eluvial (weakly weathered zone) layer has a thickness of approximately 3–5 m. Weathering develops along the rock fracture surface. The fracture surface weathering is underneath. Feldspar begins to be kaolinized. The weathering surface can peel off or break into small pieces. Weathering weakens from the crack face to the rock mass and gradually transitions to fresh bedrock. This layer belongs to the weakly weathered zone.

The parent rock is composed of giant crystals from the third stage of the Yanshan Period, phenocryst, and coarse-grained biotite granite. The rock is thick and massive. Internal factors affect the development of the thick layer of the weathering crust.

3.2 Physical and chemical properties of the collapsed wall

3.2.1 Physical properties of the collapsed wall

Table 1 shows the granularity characteristics of the collapsed wall. The composition of the soil particles at all levels in the vertical section varies significantly. All fine-grained materials, such as silt and clay particles, reinforce the debris layer of the weathering crust (weakly weathered zone), which has a proportion of more than 50%. However, the amount of silt and clay particles gradually reduce from the surface of the red soil layer (fully weathered zone) to the underlying gravel and breccia eluvial (weakly weathered zone). The clay particle content decreases more quickly than silt. The amount of clay particles at the bottom of the gravel and eluvial breccia (weakly weathered zone) layer is only 3.58%, which is approximately 1/5 of the content of red soil. Sand content increased gradually and

comprises more than 50% of the bottom gravel and eluvial breccia (weakly weathered zone) layer. The changes in grain size indicate the gradual weakening of the weathering degree from the surface layer to the bottom layer.

The natural water content, soil-saturated water content, total porosity, and soil grain of the dry density of the collapsed wall are important indexes of soil structure and condition, as indicated in Table 1. Natural water content increases with depth. Saturated water content increased to a certain value and then decreased in gravel and eluvial breccia (weakly weathered zone). The total porosity of the collapsed wall increased with depth. The density of soil particles decreased when depth increased.

3.2.2 Chemical properties of the collapsed wall

Table 1 shows that the weathering degree of the weathering crust gradually intensifies from the bedrock to the surface. The iron oxide, alumina, and titanium oxide accumulate on the surface. The amount of these materials increase with depth. Thus, the amount of Fe_2O_3 and Al_2O_3 also rises, the contents of which are several times higher than those at the bottom, making the red soil zone rich in iron and aluminium. However, silicon oxide, calcium oxide, magnesium oxide, potassium oxide, and sodium oxide all leach, and leaching intensified farther from the surface. Significant amounts of SiO_2 , CaO , MgO , K_2O , and Na_2O are leached. The underlying contents are substantially higher than those on the surface of the red soil.

Soil pH indicates the acid and alkaline levels in soil. Based on the vertical changes in the soil profile of the collapsed wall, acidity decreases when depth increases. The vertical differences in soil pH value are associated with the high amount of aluminium; H^+ , which increases soil acidity, and Al^{3+} exists. The degree of desilicification and allitization in the surface soil is high. Al^{3+} increases soil acidity. Thus, the surface of the red soil has the highest acidity.

The amount of organic matter and cation exchange capacity are important chemical properties of soil. Cation exchange capacity initially decreases but subsequently increases. Cation exchange capacity is closely correlated with soil particle composition, secondary clay mineral type, and organic matter. Cation exchange capacity is generally high when clay minerals are abundant. The cation exchange capacity in the lower part of the collapsed wall may be correlated with the high proportion of $\text{SiO}_2 / \text{R}_2\text{O}_3$ of the soil clay minerals in the lower part. The vertical changes in organic matter decrease as soil depth increases because the amount of animal and plant residue is limited at greater depths.

During the transition of the granite weathering crust of the collapsed wall from red soil to the parent material layer, the distribution of exchangeable calcium first decreases, and then subsequently increases. The amount of exchangeable sodium increases with soil depth. Sodium is a strong cation and exhibits high levels of chemical activity. In the hilly red soil region of South China, long-term desilicification and allitization on the surface soil cause alkali metals, such as Na and K, to leach and move. Leaching and movement intensify near the surface. However, Na⁺, which is found in the deep soil, has a strong ability to disperse in soil. Free iron oxide and aluminium are important indexes of the degree of rock weathering. A small amount of free iron oxide and aluminium indicates a lower degree of weathering.

3.3 Disintegration characteristics of the collapsed wall

Figures 3–6 indicate the following: at different levels of the initial soil moisture content, the order of the disintegration ratio is as follows: red soil layer < sand soil layer < clastic layer < gravel and eluvial breccia layer. The initial soil moisture content has a considerable effect on the ratio to complete the disintegration of the red soil layer and sand soil layer, with little impact on the easily disintegrated soil of the other two layers (clastic layer and gravel eluvial breccia layer). The disintegration of the clastic layer and gravel eluvial breccia layer was fully completed at any level of initial soil moisture content, so the maximum disintegration was less affected by the initial soil moisture content. After drawing and analysing the graphical sheets of the disintegration quantity of different layers at different soil moisture levels, the graphs showed that the disintegration amount presented an increasing trend with varying time.

Figure 3: Amount of disintegration of red soil layer of collapsed wall under different initial Soil Moisture Contents (SMC).

Figure 4: Amount of disintegration of sandy soil layer of collapsed wall under different initial Soil Moisture Contents (SMC).

Figure 5: Amount of disintegration of debris layer of collapsed wall under different initial Soil Moisture Contents (SMC).

Figure 6: Amount of disintegration of gravel and eluvial breccia layer of collapsed wall under different initial Soil Moisture Contents (SMC).

The disintegration characteristics of the red soil layer and sandy soil layer include the following: water absorp-

tion and bubbling occur when the samples from the red soil layer and sandy soil layer soil were placed in water. Cracks appear and disintegration gradually occurs. Figures 3 and 4 indicate that the disintegrating ratio increases when the soil moisture content in each sample decreases. The difference in the amount of disintegration with natural soil moisture content and soil moisture content after air-drying is not evident. However, the amount of disintegration dramatically increased with the natural soil moisture content. Thus, a slow disintegrating ratio indicates a high soil moisture content, and disintegration time increases with soil moisture content. The disintegrating ratios of the samples from the red soil layer and sandy soil layer gradually slowed down over time. The amount of residual soil reduced to 1/2–1/3 of the original soil and underwent a relatively static state. After a few hours, the structure completely collapsed. The preliminary disintegration occurs after 5 minutes to 40 minutes. Complete collapse requires 4 hours to 8 hours. When the natural soil moisture content is 12.43% in the red soil layer and 2.97% in the sandy soil layer, complete collapse occurs in only 40 minutes, whereas the complete disintegration of the samples occurred after four hours.

Figures 5 and 6 present the disintegration characteristics of the debris layer and gravel and eluvial breccia layer. The disintegration time of the sample increases with soil moisture content. The collapsed wall easily absorbed water and expanded in a relatively dry state, while the process was slow in the wet state. Regardless of the initial soil moisture content of the clod samples of the debris layer, complete collapse occurs within 20 minutes, which is shorter than that in the red soil layer and sandy soil layer. This result indicates that the disintegrating ratio of the debris layer soil is higher than that of the red soil layer and sandy soil layer. Thus, the corrosion resistance of the debris soil layer is weaker than that of the red soil layer and sandy soil layer. The disintegration ratio of gravel and breccia is short. Absorption is intense when the clod is placed in water. All the structures completely collapse within five minutes regardless of initial soil moisture content. The increase in the disintegration ratio is slightly lower than that in the soil moisture content of the clod. The clod disintegration of the samples of the debris layer and gravel and eluvial breccia significantly differs from that of the red soil layer and sandy soil layer. The red soil layer and sandy soil layer first disintegrate into several small lumps. These layers can maintain small clumps in a relatively static state for a long time, whereas the soil particles of the debris layer and gravel and eluvial breccia layer are thinly dispersed directly from the inside to the outside, which indicates that the disintegration characteristics of

the debris layer and gravel and eluvial breccia are significantly more intense than that of the red soil layer and sandy soil layer.

3.4 Influence of factors on disintegration characteristics of the collapsed wall

The correlation coefficients were determined by conducting a correlation analysis on natural water, physical and chemical properties of the collapsed soil, and amount of disintegration (disintegrating ratio) after 1, 2, 5, and 10 minutes. The results are presented in Table 1. Most of the physical and chemical properties of the collapsed wall are significantly correlated with disintegrating ratio. Only the exchangeable calcium, saturated water content, soil density, and dry density of soil particles are not significantly related to disintegrating ratio. As disintegration occurs, the influence of each factor decreases. Some factors do not exhibit a significant effect on disintegration after 5 and 10 minutes. These factors include cation exchange capacity, free alumina, Na_2O , free iron oxide, and porosity, which may cause the samples of the debris layer and gravel and eluvial breccia to completely collapse in 10 minutes. The following factors, which are positively correlated with the disintegration ratio, are arranged from their highest to lowest correlation coefficient: sand content, MgO , natural water content, K_2O , CaO , exchangeable sodium, pH, porosity, Na_2O . The following factors, which are negatively correlated with the disintegrating ratio, are arranged from their highest to lowest correlation coefficient: clay particle, Fe_2O_3 , silt particles, Al_2O_3 , TiO_2 , and SiO_2 , organic matter, free iron oxide, and free alumina. The correlation coefficients indicate that the disintegrating ratio is closely associated with soil particle size, Fe_2O_3 , natural water content, and chemical composition of clay minerals. Future studies must analyse how these factors affect disintegration.

4 Discussion

The results of the current and previous studies show that the top layers of collapsed walls of soil (red soil, sandy soil layer) are prone to fracture, and the degree of fracture is high for the bottom layers (debris layer, gravel and eluvial breccia layer) [5, 9]. Rain easily penetrates the deep layers (debris layer, gravel and eluvial breccia layer) through cracks. The infiltration and movement of water along the trench wall exposes the different layers

of soil, which cause the soil to absorb water, swell, and disintegrate. Gravel and eluvial breccia layers at the bottom are the most prone to collapse and movement with the addition of water. Thus, the overlying red soil layer and sandy soil layer exist in a suspended state. However, cracks and other openings exist in the upper red soil layer and sandy soil layer; thus, the soil easily disintegrates and collapses because of the dynamic pressure of seepage flow. The erosion gully continuously expands, whereas the edge of the collapse mound extends upward, thereby resulting in the rapid development of the collapsed mound. When the head of the erosion gullies of the collapsed mound is close to or reaches a watershed, precipitation and infiltration water can alter the processes in the soil, although the effect of direct runoff scouring can be disregarded. Thus, collapse is inevitable. If soil erosion in the middle and upper slopes occurs because of the combined action of soil collapse after the absorption of water and washing, the disintegration of the collapsed wall is mainly attributed to soil suction when the head of erosion gullies is near a watershed. This explanation also verifies actual occurrences. When a thin red soil layer is penetrated and eroded by runoff, the disintegration of the collapsed mound intensifies and is thus difficult to control. When the soil openings dangle at the bottom of the surface of the collapsed wall, the lower part of the collapsed wall undergoes the following cyclical process: rainfall disintegration and digging → collapse to form dangling soil → collapse → penetration into deep layers. In this cycle, the gully head in all directions is close to or reaches a watershed, and the edge of the collapsed mound and colluvial pile forms a stable slope and equilibrium profile at the bottom of the form. Future studies must elucidate the influence of the physical and chemical properties of collapsed walls on disintegration, permeability, and soil strength. The effect of soil moisture on collapsed walls and dangling height on the stability of the wall must be determined. To clarify the erosion mechanism of Benggang erosion and identify effective control measures, collapse erosion theory must be expanded. The red soil layer must be protected to effectively control mound collapse.

5 Conclusion

1. The physical and chemical properties of the four layers of soil samples of a collapsed wall (red soil layer, sandy soil layer, debris layer, gravel, and breccia eluvial) are closely related to the weathering degree of the weathering crust.

2. Gravel and eluvial breccia exhibited the fastest disintegration on the vertical section of the collapsed wall, whereas the red soil was the slowest. The order of the disintegrating ratio of the layers are as follows: red soil layer < sandy soil layer < debris layer < gravel and eluvial breccia. Initial water content significantly affects the disintegrating ratio of the red soil layer and sandy soil layer, whereas this factor slightly influences the debris layer and gravel and eluvial breccia.
3. Most of the physical and chemical properties of the collapsed wall are significantly correlated with the disintegrating ratio. The order of the correlation coefficient of these properties from highest to lowest is as follows: sand content, MgO, natural water content, K₂O, CaO, exchangeable sodium, pH, porosity, Na₂O, and cation exchange capacity. The following physical and chemical properties of the collapsed wall, which are significantly correlated with the disintegrating ratio, are arranged from their highest to lowest correlation coefficient: cosmid, Fe₂O₃, silt particle, Al₂O₃, TiO₂, SiO₂, organic matter, free iron oxide, and free alumina. Only the exchangeable calcium, saturated water content, specific gravity of soil particle, and dry density of soil particles are not significantly correlated with the disintegrating ratio. The correlation coefficients indicate that the disintegrating ratio is closely associated with soil structure and the chemical content of clay minerals. Further supplementary testing and analysis must be conducted in the future to determine the content and form of exchangeable sodium, calcium, and secondary clay minerals and subsequently analyse how the dispersion of sodium, calcium cementation, and clay minerals affects the erosion of collapsed walls.

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References

- [1] Xu J.X., Benggang erosion: the influencing factors. *Catena*, 1996, 27, 249-263.

- [2] Xu J.X., Zeng G.H., Benggang erosion in sub-tropical granite weathering crust geo- ecosystems: an example from Guangdong Province. In: D.E. Walling et al. (Editor), *Erosion, Debris Flows and Environment in Mountain Regions*, IAHS Publication, 1992, 209, 455–463.
- [3] Luk S.H., Yao Q.Y., Gao J.Q., Zhang J.Q., He Y.G., Huang S.M., Environmental analysis of soil erosion in Guangdong Province: a Deqing case study. *Catena*, 1997, 29, 97-113.
- [4] Jiang F.S., Huang Y.H., Wang M.K., Lin J.S., Zhao G., Ge H.L. , Effects of rainfall in tensi and slope gradient on steep colluvial deposit erosion in Southeast China. *Soil Science Society of America Journal*, 2014, 78, 1741-1752.
- [5] Zhou H.Y., Li H.X., The impact of soil cracks development on the collapsing hill erosion in weathered granite shell of South China. *Jangsu agricultural science*, 2014, 42, 352-354 (in Chinese with English abstract)
- [6] Liu X.L., Tang X., Zhang D., Simulated runoff processes on colluvial deposits of Liantanggang Benggang and their water distributions. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2015, 31, 179-185 (in Chinese with English abstract)
- [7] Wu Z.F., Wang J.Z., Relationship between slope disintegration and rock- soil characteristics of granite weathering mantle in south China. *Research Soil and Water Conservation*, 2000, 14: 31-35 (in Chinese with English abstract)
- [8] Li S., A study on characteristics of rock-soil and countermeasures of the collapsed mound formation. *Journal of Soil Water Conservation*. 1992, 6, 29-35 (in Chinese with English abstract)
- [9] Zhou H.Y., Li H.X., Ye Q., Wu G.W., Simulation of Morphological Development of Soil Cracks in the collapsing hill soil region of Southern China. *Research of Soil and Water Conservation*, 2016, 23, 338-342 (in Chinese with English abstract)
- [10] Lin J.S., Zhuang Y., Huang Y.H., Jiang F.S., Lin J.L. Ge H.L., Shear strengths of collapsing hill in red soil as affected by soil moisture under different experimental methods. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2015, 31, 106-110 (in Chinese with English abstract).
- [11] Yan B., Tang L.S., Hu H., The mechanism of disintegration damage of granite weathered soil. *Hydrogeology & Engineering Geology*, 2009, 36, 68-71 (in Chinese with English abstract)
- [12] Niu D., Research on the Environmental Factors and Erosion Mechanism of Collapsing Hill in South China. Ph.D. Thesis, Nanjing Forestry University, China, 2009 (in Chinese with English abstract)
- [13] Liu D.L., Zhao Y., Ding S.W. Deng Y.S., Wang Q.X., Lyu G., Correlation between initial soil moisture content and the characteristics of collapsing gullies in granite regions. *Science of Soil and Water Conservation*, 2016, 14, 17-22 (in Chinese with English abstract)
- [14] Zhang S., Tang H.M., Experimental study of disintegration mechanism for unsaturated granite residual soil. *Rock and Soil Mechanics*, 2013, 34, 1668-1674 (in Chinese with English abstract)
- [15] Lan Z.X., Experimental study on disintegration behaviour of granite residual soil. PhD thesis, South China University of Technology, China, 2013 (in Chinese with English abstract)
- [16] Nanjing Institute of Pedology, Chinese Academy of Sciences (ed.), *Analysis of Soil Physical and Chemical Properties*. Shanghai Science and Technology Press, China, 1978 (in Chinese)