Quantification of red soil macropores affected by slope erosion and sediment using computed tomography

Authors: Si-Yi Zhang, Bin He, Yan Sun, Fan-Ling Kong, Wan-Yi Huang, Bin He

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Abstract

Purpose Soil structure is the primary driver of the formation and development of collapsing gullies, which represent the most severe type of erosion in southern China. However, few studies have focused on the relationship between soil macropores, soil erosion, and local topography. This study aimed to quantify and compare soil properties and macropore characteristics in the collapsing gully region, and explore their influences on the formation and development of associated erosion processes.

Materials and methods Soil core columns at different positions of a typical collapsing gully were excavated and then scanned to analyze soil macropores. Moreover, soil properties and saturated hydraulic conductivity were investigated in the laboratory and in the field, respectively.

Results and discussion The results indicated that sand content increased from the ridge to the slope and valley, while silt and clay contents decreased along the same catena. The mean weight diameter of aggregates was largest at the ridge and smallest at the valley. Infiltration rates were highest at the valley and lowest at the slope. The valley exhibited the greatest macroporosity (1.09$±0.33±703), volume(24.7±7.5cm3), andsurfacearea(10.4±2.6m2)ofmacropores, aswellasthehighestcon
The number of macropores and their macroporosity generally decreased with increasing depth, but were influenced by soil macrofauna as well as erosion and sedimentation processes. Macropores were predominantly vertical, influenced by plant roots and facilitating vertical water infiltration. However, numerous horizontal macropores were present at the valley due to sedimentation processes. The equivalent pore diameter of macropores was predominantly smaller than 2 mm (accounting for more than 76.3%), and macropores larger than 5 mm constituted less than 1%.

Conclusions The macropore characteristics at different sites of collapsing gullies affected soil water infiltration and hydraulic conductivity, and consequently influenced water erosion and mass erosion processes. The highest macroporosities at the valley would result in strong subsurface flow erosion and loss of the collapsing wall base. Macropores at the ridge would increase rainfall infiltration and promote soil collapse. Few macropores and low infiltration capacity at the slope would strengthen overland flow erosion. Thus, macropore characteristics had significant effects on both the formation and development of collapsing gullies.

Full Text

Quantification of Red Soil Macropores Affected by Slope Erosion and Sediment Using Computed Tomography

Si-Yi Zhang[1],[2], Bin He[1],[2]*, Yan Sun[1],[2], Fan-Ling Kong[1],[2], Wan-Yi Huang[1],[2]

[1] National-Regional Joint Engineering Research Center for Soil Pollution Control and Remediation in South China, Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Institute of Eco-environmental and Soil Sciences, Guangdong Academy of Sciences, Guangzhou 510650, China

[2] Guangdong-Hong Kong-Macao Joint Laboratory for Environmental Pollution and Control, Guangzhou 510650, China

* Correspondence: bhe@soil.gd.cn

Abstract

Purpose: Soil structures are the main cause of the formation and development of collapsing gullies, which represent the most severe type of erosion in South China. However, few studies have focused on the relationship between soil macropores, soil erosion, and local topography. This study aimed to quantify and compare soil properties and macropore characteristics in a collapsing gully region, and explore their influences on the formation and development of associated erosion.

Materials and methods: Soil core columns at different positions of a typical collapsing gully were excavated and scanned to analyze soil macropores. Moreover, soil properties and saturated hydraulic conductivity were investigated in the laboratory and in the field, respectively.

Results and discussion: The results indicated that sand content increased from the ridge to the slope and valley, while silt and clay contents decreased across the same catena. The mean weight diameter of aggregates was largest at the ridge and smallest at the valley. Infiltration rates were highest at the valley and lowest at the slope. The valley exhibited the greatest macroporosity $(1.09\$\pm0.33\pm703), volume(24.7\pm7.5cm^{\{3\}), andsurfacearea(10.4\pm2.6m}\{2\})ofmacropores, aswellasthehighestconn$ was largest at the ridge $(16.8\$\pm7.4) andsmallestattheslope(10.6\pm\$2.9)$. The number of macropores and their macroporosity generally decreased with increasing depth, but were influenced by soil macrofauna as well as erosion and sediment processes. Macropores were mainly vertical, influenced by plant roots and conducive to vertical water infiltration. However, many horizontal macropores existed at the valley due to sediment processes. The equivalent pore diameter of macropores was predominantly smaller than 2 mm (accounting for more than 76.3%), while macropores larger than 5 mm constituted less than 1%.

Conclusions: The macropore characteristics at different sites of collapsing gullies affected soil water infiltration and hydraulic conductivity, which further influenced water erosion and mass erosion processes. The highest macroporosities at the valley would result in strong subsurface flow erosion and loss of the collapsing wall base. Macropores at the ridge would increase rainfall infiltration and promote soil collapsing. Few macropores and low infiltration capacity at the slope would strengthen overland flow erosion. Thus, macropore characteristics had significant effects on both the formation and development of collapsing gullies.

Keywords: Soil macropores; computed tomography; erosion; sediment; collapsing gully

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1. Introduction

Collapsing gullies, locally called "Benggang," represent the most extensively eroded areas across seven provinces in South China. Both mass erosion and water erosion occur synergistically on the weathering crust of granite, at depths ranging from dozens to hundreds of meters, in tropical and subtropical regions. This region contains more than 2.4×10^{5} collapsing gullies, covering an area of 1.1×10^{3} km^2 (Figure 1a [Figure 1: see original paper]), with 45% located in Guangdong Province, which accounts for 74% of their total area (Liang et al., 2009). More than 6.7×10^{7} t yr^{-1} of soil is lost due to these collapsing gullies, damaging farmland, houses, roads, bridges, reservoirs, and ponds, and causing economic losses of 3.2×10^{9} USD, affecting 9.2×10^{6} residents (Liang et al., 2009). The mechanisms of occurrence and development of collapsing gullies have attracted considerable research attention, with soil macropores and soil water movement considered important factors (Tao et al., 2020).

Many factors influence the spatial distribution and movement of soil water and other hydrological processes (Ghasemizade and Schirmer, 2013). Soil properties that particularly affect hydrological processes include soil structure, particle size distribution, porosity, soil layer characteristics, oxidation-reduction properties, organic matter content, soil water repellency, and soil water content itself (Zhu et al., 2012). Among these factors, the influence of macropores on soil water movement is of key importance (Lin et al., 2010). Macropores allow rainfall to infiltrate into deeper soil layers, while impervious layers without macropores, such as caliche, prevent continuous water infiltration, leading to higher soil water content above the caliche (Zhang et al., 2012; Li et al., 2013; Hu et al., 2018). The macropore structures of soil differ across slope positions due to variations in soil aggregate characteristics, gravel content, and plant roots, resulting in differences in soil water conductivity and preferential flow characteristics (Holden, 2009; Zhang et al., 2016; Mei et al., 2018; Hu et al., 2020a). However, preferential flow forms different macropore structures due to erosion (Nguyen et al., 2019).

The tropical and subtropical regions of South China experience frequent storms with obvious alternations between dry and wet periods. Water is the limiting factor for ecosystem service functions during the dry season and the driving factor for collapses, landslides, debris flows, and other disasters during the rainy season (Liang et al., 2014; Tang et al., 2014). The granite weathering crust in the study area can be divided from top to bottom into a topsoil layer, red soil layer, sand layer, debris layer, and spherical weathering layer (Tao et al., 2017). It has been reported that the infiltration capacity of the red soil layer, sand layer, and debris layer decreases sequentially from the surface to deeper layers (Duan et al., 2018). The water holding capacity of the topsoil layer and red soil layer is stronger than that of the sand layer and debris layer. Soil water content gradually increases from top to bottom within the topsoil layer; however, it gradually decreases from the red soil layer to the debris layer. The farther a site is from the collapsing wall, the higher its soil water content (Yusong et al., 2015; Ni, 2016). Preferential flow varies by slope position and soil layer (Tao et al., 2017). More preferential flows occur in the red soil layer than in the sandy soil layer and clastic layer (Zhao, 2016), affected by soil properties, precipitation characteristics, and initial water content (Duan et al., 2016). Currently, studies on soil hydrology of collapsing gullies focus mostly on hydrological characteristics and processes, or on physical and chemical soil properties. However, little research addresses the comprehensive effects of geomorphology, vegetation, and soil properties, or their influence mechanisms on soil hydrological processes. Therefore, the influence of soil macropore structure on soil hydrological processes, the mechanisms of spatial distribution and transport of soil water, and their responses to future climate change are not fully understood.

The loose and deep granite crust forms the material basis of collapsing gullies, while both rainstorms and soil water accumulation are the main drivers of their development. Soil structural properties (e.g., soil particle composition, bulk density, and porosity) vary significantly across different layers of the deep granite crust (Liao et al., 2018), resulting in greatly differing soil mechanical characteristics in response to wetting (Xia et al., 2018). Increased soil water content after rainfall and infiltration leads to increased upper soil weight and decreased soil shear resistance, which in turn results in collapse of the granite soil wall (Zhang and Zhong, 1990). Simultaneously, decreased cohesion and internal friction angle of granite soil, along with increased pressure of soil fissure flow when subjected to water, are the main causes of granite soil wall collapse (Li, 1992). Preferential flow along soil macropores is considered an important reason for the spatiotemporal variation of soil water content and soil fissure water movement (Hencher and Beven, 2010).

Therefore, studying soil macropores in granite red soil is of great practical importance, as it aids investigations of hydro-pedological processes toward a better understanding of the occurrence and development patterns of collapsing gullies. This study also helps to effectively prevent, control, and restore erosion-related damage in these regions.

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2.1. Study Sites

Soil cores were sampled at a collapsing gully in Huacheng Town (24°04 N, 115°38 E), north of Wuhua County, Guangdong Province, China (Figure 1). Collapsing gullies are often close to residential and agricultural regions, and the frequently devastating soil erosion and mud-sand flow events (Zhang and Liu, 2014) increase risks to houses, roads, and farmlands (Figure 1b). Wuhua County is a representative subtropical monsoon region with a mean annual air temperature of 21.3 °C and mean annual precipitation of 1507.2 mm (Zhang et al., 2020). The soil parent material is biotite granite with very deep weathering crusts, often exceeding 200 m. The soil is barren sandy loam with only 1.71 g kg^{-1} soil organic carbon (Zhang et al., 2020). The vegetation is secondary with coverage varying from 20% to 80% under different topographic and erosion conditions (Figure 1b). *Pinus massoniana* is the dominant constructive species, while *Dicranopteris dichotoma*, *Rhodomyrtus tomentosa*, *Miscanthus floridulus*, and *Baechea frutescens* form the main undergrowth (Zhang et al., 2020). Three sites along a slope near a Benggang—the ridge site, slope site, and valley site (Figure 1b)—were selected, and a total of nine undisturbed soil cores were collected in three replicates per site. The ridge and slope sites were covered by sparse *P. massoniana* with rare undergrowth vegetation, whereas the valley site was mainly covered by *Phyllostachys edulis* with dense *D. dichotoma* and *Nephrolepis auriculata* as undergrowth. <Figure 1>

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2.2. Analysis of Basic Soil Properties

For each site, three replicated soil samples were collected and analyzed for soil properties. Soils were air-dried at room temperature before sieving to 2 mm to determine particle size distribution using the pipette method (Gee and Bauder, 1986). Aggregate size distribution was measured by separating different aggregates via wet sieving following a previously published method (Dong, 1997). First, field-moist soil samples were carefully passed through an 8-mm sieve (without breaking the soil structure) and then air-dried. Approximately 50 g of air-dried soil from each replicate was wet-sieved through a series of four sieves, separating samples into five aggregate size fractions: >2000 m large macroaggregates, 1000–2000 m middle macroaggregates, 500–1000 m small macroaggregates, 250–500 m tiny macroaggregates, and 106–250 m microaggregates. The four sieves were stacked with the largest at the top and smallest at the bottom, and the soil sample was placed in the top 2-mm sieve. Before wet-sieving, samples were immersed in water on the top sieve for 5 min to break down aggregates via slaking pressure. Sieving was controlled by an Aggregate Analyzer (QT-WSI021, Qudaotech, Shanghai, China) with an up-and-down movement frequency of 30 times per minute for 2 min. After sieving, each sieve was backwashed and the retained fraction was collected, oven-dried at 105 °C, and weighed. The mean weight diameter (MWD) was computed as the sum of the oven-dried mass fraction remaining in each sieve multiplied by the mean diameter of adjacent meshes (Le Bissonnais, 1996).

2.3. Field-Saturated Soil Hydraulic Conductivity Measurements by DualHead Infiltrometers

Field-saturated soil hydraulic conductivity (Kfs) was measured using a DualHead Infiltrometer (Decagon Devices, Pullman, WA, USA) following an optimized method of Zhang et al. (2019). Before data collection, grass and vegetative litter were carefully removed and surface soil temperature and water temperature were measured using ECH$_2$O 5TE sensors (Meter Group, Pullman, WA, USA). An insertion ring with 5 cm depth and 7.5 cm radius was gently driven into the soil to ensure good contact and minimize disturbance, with the ring leveled in all orthogonal directions. Kfs was measured using a single cycle with 35 min holding time at pressure heads of 10 and 15 cm after 15 min of soaking. Only measurements without leakage and with coefficients of variation for pressure head and water level below 15% were considered reliable for further analysis. All Kfs values were viscosity-corrected to a standard temperature of 25 °C before comparison among sites, preventing the influence of changes in water effluent viscosity at different temperatures according to a previously described method (Zhang et al., 2019).

2.4. Soil Core Samples

Polyvinyl chloride (PVC) cylinders with 5-mm wall thickness, 10-cm diameter, and 50-cm length were used to house intact soil. After plot selection, aboveground grass (if present) was clipped to ground level and litter removed to expose bare soil before sampling. The PVC cylinder was pushed into the soil using the instrument shown in Figure 2 [Figure 2: see original paper]. First, the ground spears (8) were revolved into the ground and the support system (7, 6) was set up. An air-bubble level (9) was affixed to the top of the iron roof plate (6) to ensure it was level. A steel tube (1) under the roof housed a PVC cylinder (4) with a window (2) on the upper side. The internal diameter of the steel tube (1) was only marginally larger than the external diameter of the PVC cylinder to limit shifting. A steel cap was affixed to the top of the PVC cylinder. A vertical hydraulic jack (3) was then inserted between the roof (6) and steel cap through the window (2) of the steel tube (1). The PVC cylinder (4) was pressed into the soil by driving the hydraulic jack (3) while the roof (6) was fixed by struts (7) and ground spears (8). When the hydraulic jack (3) reached its maximum lifting limit, it was removed and reset. A log (5) with the same diameter as the PVC cylinder (4) and height below the maximum lifting limit of the hydraulic jack (3) was placed on the steel cap. The hydraulic jack (3) was reinserted into the window (2) and driven again. These operations were repeated until the entire PVC cylinder (4) had penetrated the soil. To reduce resistance from the soil layer, plant roots were cut, and to avoid damage from gravel, a steel ring knife (10) was installed at the bottom of the PVC cylinder. The inner diameter of the front blade of this steel ring knife was identical to the inner diameter of the PVC cylinder. The inside of the upper end of the ring knife featured a groove whose inner diameter equaled the outer diameter of the PVC cylinder (4). Two small vertical windows at the bottom of the steel tube (1) allowed observation of whether the PVC cylinder (4) had been completely pressed into the soil. This instrument smoothly and vertically pushes the PVC cylinder into the soil without shock or rotation, thus obtaining soil cores with minimal disturbance. After sampling, the PVC cylinder was extracted, capped at each end with PVC caps, and wrapped in sponge to protect the soil from mechanical disturbances. <Figure 2>

2.2. X-Ray Computed Tomography Scanning and Image Analysis

A Philips Medical Scanner (Royal Dutch Philips Electronics Ltd., Model: iCT 256, Amsterdam, Netherlands), a 256-slice spiral X-ray computed tomography (CT) scanner, was used to scan the obtained soil cores. The energy level was set to 140 kV and X-ray tube current to 153 mA. Scanning was continuous with a slice thickness of 0.67 mm and scan interval of 0.3 mm. After scanning and reorientation, an image sequence was produced with more than 1667 slices for each soil core in coronal view. Voxel Cone Tracing acquired 16-bit, 1024$×$1024 images with voxel dimensions of 0.122 mm × 0.122 mm × 0.3 mm (width × length × depth).

Images were analyzed using ImageJ software version 1.4.3.67 to examine pore characteristics according to the following steps: (1) **Slice selection:** To avoid voids and minimize disturbance from sampling, 100 slices (3 cm depth) at the soil core head and 60 slices at the soil core end were removed using the "Slice Remover" tool in ImageJ, leaving 1500 slices (45 cm depth) for analysis. (2) **Region of interest selection:** The "Region of Interest" tool excluded voids near core walls and minimized beam hardening effects. A central square area with 80 mm diameter was selected as the region of interest and cropped for further analysis. (3) **Thresholding:** Attenuation values of obtained images ranged from -1024 to over 3071. The intensity value of water phantoms (mean = 0) was set as the threshold to differentiate air-filled spaces from other regions. Values below the threshold were identified as air-filled pores, while values above were identified as non-pores (Feng et al., 2003; Hu et al., 2015). This threshold was also used by Udawatta et al. (2008) and performed well in this study. Small PVC cylinders with known diameters were inserted into an undisturbed soil core and scanned, enabling interpretation of pore sizes through this threshold analysis. After thresholding, images were converted to binary images where black areas represent the soil matrix and white areas represent macropores. (4) **Macropore analysis:** After segmentation, soil macropore connectivity was estimated using the "Purify" and "Connectivity" plugins of ImageJ. The numbers of macropores, macropore area, macropore perimeter, circularity, feret, and minimum feret of each slice were calculated using the "Analyze Particles" tool in 2D. Slice porosity was calculated by dividing pore area by soil core area (5024 mm^2).

Previous studies classified pores with equivalent pore diameter (ϕ) > 0.1 mm as macropores (e.g., Harvey and Nuttle, 1995), so pores detected using CT (at 0.122 mm × 0.122 mm resolution) could all be defined as macropores. Other researchers reported that only pores with $\phi > 1$ mm should be classified as macropores (Carey et al., 2010); therefore, this study classified pores with $\phi >$ 1 mm as wide macropores for better distinction.

The numbers of macropore tubes, macropore volumes, and macropore surface areas were calculated with the "3D objects counter" plugin. These 3D pores were divided into wide macropores or macropores depending on whether volumes exceeded 1 mm^3. Three-dimensional visualization of soil macropore networks was reconstructed using the "3D viewer" plugin, and the skeleton of 3D soil macropore networks was established using the "Skeletonise 3D" plugin. The numbers and lengths of macropore tubes and their branches were analyzed using the "Analyse skeleton" plugin. <Figure 3 [Figure 3: see original paper]>

2.3. Statistical Analyses

Differences among measured parameters within-group sites were analyzed using one-way analysis of variance (ANOVA) combined with Fisher' s protected least significant difference (LSD) test. All statistical analyses were conducted using SPSS software (version 19.0, IBM Inc., USA) at a confidence level of $p = 0.05$.

3.1. Soil Properties

Soil properties varied greatly across the investigated catena from ridge to valley (Table 1). Soils were clay loam, loam, and sandy loam at the ridge, slope, and valley, respectively. Sand content increased from ridge to valley, while clay content followed the opposite trend, and silt content was highest at the slope. Bulk densities at the ridge were insignificantly higher than at the slope, while bulk densities at both sites were significantly higher than at the valley floor for all depths. Total porosity differences contrasted with bulk density patterns. Capillary porosity increased from ridge to valley but only showed significant differences between ridge and valley at 20-40 cm depth. No significant differences were found in non-capillary porosity of 0-20 cm soil layers across sites; however, at 20-60 cm depth, non-capillary porosity at the valley was significantly higher than at both ridge and slope. Saturated soil moisture increased from ridge to valley, though field water capacity only showed significant differences at the 20-40 cm layer. Aggregate weight percentages and MWD increased from ridge to valley. Kfs values at ridge and slope sites were 135.7 ± 98.7 and 80.6 ± 56.1 mm h^{-1}, respectively. Ridge sites had higher Kfs than slope sites, but differences were not significant ($p = 0.449$). Kfs at the valley could not be measured as it exceeded the maximum measurement range of the DualHead Infiltrometer (1150 mm h^{-1}).

3.2. Visualization of Macropore Networks

Visualizations of soil macropore networks in soil columns are shown in Figure 4 [Figure 4: see original paper]. Soils at the valley exhibited the greatest macroporosity and more macropores than soils at the ridge; however, soils at the slope had minimum macroporosity and macropores. At the ridge and slope, soil macropores were mainly distributed in the surface layer (0-15 cm), where they formed networks, while deeper soil layers (>15 cm) contained fewer and more isolated macropores. Exceptionally, the Ridge #3 soil core showed many macropores at 15-35 cm depth because this sample contained an ant nest. Valley soil columns showed high macroporosity at all depths (Valley #3). Sometimes, macropores in deeper layers (30-40 cm) showed higher numbers than in shallower layers (0-15 cm, Valley #2). Macropore directions at the ridge and slope were mainly vertical with few horizontal networks at the surface layer; however, macropore directions at the valley were mainly horizontal, differing from the other two sites.

3.3. CT-Measured Macropores and Macroporosity of Whole Columns

The total number, volume, and surface area of soil macropores, as well as macroporosity at the valley, were significantly higher than at the ridge and slope (Table 2). Wide macroporosities (volume > 1 mm^3) were 3.3 ± 1.9%, 1.4 ± 1.4%, and 10.5 ± 3.3% for soil columns at the ridge, slope, and valley, respectively, with wide macropore numbers (volume > 1 mm^3) of 428 ± 75, 266 ± 188, and 1468 ± 194, respectively. Although wide macropores constituted only a small portion of total macropores detected by CT, large macropore volumes and wide macroporosity accounted for the majority of total macropore volume and macroporosity. Mean macropore volume and mean surface area showed no significant differences between sites. Mean connectivity differed greatly among sites (Table 2); however, differences were insignificant due to large variations within each site.

3.4. Spatial Distribution of Macropores

Large variations occurred in macropore number distribution along depth for different sites (Figure 5 [Figure 5: see original paper]). Although trends differed among replicates, the average trend of macropore numbers decreased with increasing soil depth. In the top 3 cm of soil cores, wide macropore numbers were 11.4, 10.4, and 27.5 at the ridge, slope, and valley, respectively. At the ridge, average wide macropore number decreased to 7.4 at 3-6 cm depth and ranged between 4.8 and 3.7 at 33-45 cm depth. At the slope, average wide macropore number decreased to 3.8 at 6-9 cm depth and remained between 1.9 and 3.2 at 27-45 cm depth. Wide macropore numbers at the valley were highest among the three sites, with a maximum of 27.7 at 3-6 cm depth. Total macropore numbers also decreased with increasing depth (Figure 5). The percentage of wide macropores to total macropores increased with soil depth at both ridge and valley.

Soil macroporosities differed greatly among the three investigated sites (Table 2) and also varied with depth based on slice data (Figure 6 [Figure 6: see original paper]). Soil macroporosities generally decreased with increasing soil depth except for Ridge #3 and Valley #2. In the top 3 cm of analyzed soil cores, mean macroporosities were 0.62%, 0.48%, and 2.04% for ridge, slope, and valley, respectively. Macroporosities at the ridge remained above 0.50% over 12 cm depth, then fell below the mean macroporosity of 0.34% except at 15-18 cm and 30-33 cm depths where extended ant nests were accidentally sampled in

Ridge #3. Ant nests are common in this region and their inclusion in samples cannot be avoided. At the slope site, only macroporosities in soil layers above 9 cm depth exceeded 0.48%, and macroporosities in layers below this depth did not exceed 0.16%. Macroporosities in the valley were highest among the three sites for each layer, ranging from 0.27% to 1.33% at depths below 18 cm. Trends in wide macroporosities were similar to those of macroporosities (Figure 6) since wide macropores represent the majority of total macropore volume (Table 2).

3.5. Macropore Size Distribution

Macropore sizes (ϕ) mainly ranged between 0.1–1 mm and 1–2 mm, accounting for more than 44.0% and 32.3%, respectively (Figure 7 [Figure 7: see original paper]). Macropores with $\phi > 5$ mm constituted less than 1% of total macropores at all three sites. At the slope site, the percentage of 0.1–1 mm macropores was highest among the three sites, while percentages of wide macropores larger than 2 mm were lowest. Percentages of 1–4 mm wide macropores at the valley were highest among the three sites, while percentages of wide macropores >4 mm were highest at the ridge.

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4. Discussion

Macropore networks differed distinctly among different positions in collapsing gullies, and different macropore types were detected by CT. Earthworm-formed macropores are highly continuous, relatively large, and tubular (Luo et al., 2010); however, earthworms were not found at the ridge and slope since the soil was very barren with soil organic carbon as low as 1.71 g kg^{-1} (Zhang et al., 2020). A network of ant nests was unexpectedly found in the middle of Ridge #3 (Figure 4). Ant network macropores were characterized by several large chambers connected by tunnels, similar to characteristics observed previously (Li et al., 2017; Li, 2017). Root-formed macropores were highly continuous and round, with size generally decreasing with depth. These macropores were found in all soil cores, especially within the top 10 cm, consistent with roots being mainly distributed in the topsoil layer. Smaller, more randomly distributed, and less continuous macropores were likely inter-aggregate macropores formed by wetting and drying cycles (Luo et al., 2010; Hu et al., 2015). These represent the main macropores in soil layers deeper than 20 cm at ridge and slope sites. Another phenomenon is the presence of many horizontal macropores at the valley site, occurring because plants generally have shallow roots that grow horizontally (e.g., bamboo) due to high soil water levels and absence of water deficits in the valley.

Erosion and sediment processes greatly affected the number, size, macroporosity, and continuity of soil macropores. Soil macropores at the slope were comparatively rare and small (Table 2), similar to previous findings by Zhang et al. (2016). Soil erosion was more intensive at the slope compared to the ridge (Sabzevari and Talebi, 2019), and soil horizon A at the slope had eroded during observation. Soil horizon A usually has higher porosity and more macropores than horizon B (Hu et al., 2020b). The barren slope soil without horizon A also restricted plant growth, and the *P. massoniana* growing there were aged and dwarfed without undergrowth, further limiting macropore development. At the valley, however, soil was deposited by floods from the slope, and many dead tree branches were buried in different layers, forming macropores after decomposition. Additionally, the sediment consisted mainly of sand with abundant inter-aggregate macropores.

Macropore characteristics varied across sites, affecting soil water movement and erosion processes. At the slope, few macropores limited infiltration capacity (Iversen et al., 2012; Hu et al., 2020a). Superimposing flow from upslope, overland flow at the slope was strong and erosive. Severe erosion limited soil water due to minimal infiltration, and soil barrenness caused by horizon A loss inhibited plant establishment. Thus, the interaction between low macropore numbers, low vegetation cover, and intense overland flow was mutually reinforcing. The development of slope erosion thus extends into collapsing gullies, representing one evolutionary mechanism after destruction of original vegetation. This agrees with previous literature proposing that collapsing gullies developed due to vegetation loss (Zhang and Zhong, 1990).

The ridge had more macropores that were larger in size and volume, with macroporosity also higher than at the slope. This resulted from relatively weaker soil erosion and better vegetation conditions at the ridge compared to the slope. Plant root and soil macrofauna (e.g., ant) activities are advantageous for macropore formation. These conditions promote water infiltration at the ridge. According to previous research, soil water content is an important factor promoting development of existing collapsing gullies (Shi, 1984; Li, 1992). Increased rainfall infiltration decreases shear resistance of the soil layer while adding to soil column weight, further increasing the probability and risk of soil collapse and gully development. Macropores decreased with increasing soil depth, indicating that infiltration ability decreases with depth as reported by Duan et al. (2018). Thus, soil water would remain in the topsoil layer, increasing soil layer weight and decreasing shear resistance (Deng et al., 2018).

The valley site was covered by sediment from upslope and had abundant macropores. Consequently, infiltration would be large and subsurface flow may be strong under these conditions. High soil water content and subsurface flow increase the risk of subsurface flow erosion (Tebebu et al., 2010). The sediment was sandy, containing little clay. Alluvial sediment is very erosive when vegetation cover is insufficient (Jiang et al., 2020). As observed in the field, once the check dam was completely filled, overland flow could easily erode the inside sediment and form a deep gully. Once sediment was removed, the base of the collapsing wall would be lost, increasing collapse risk without base support.

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5. Conclusions

This study quantified macropore features of soil using CT at different sites in a collapsing gully region. The results provided macropore information about effects of soil erosion and sediment on soil structure and clarified aspects of their interaction. The ridge had more and larger macropores than the slope, while valley sediment had the most macropores. Macropore numbers and macroporosities mostly decreased with increasing soil depth. Equivalent pore diameter of macropores mainly remained below 2 mm. These characteristics differed according to tomography position, soil erosion, plant cover, and soil macrofauna. High macroporosities at the valley and ridge increased risks of subsurface flow erosion and soil collapse, promoting collapsing gully development. Soil macropores at the slope were rare and infiltration capacity was comparatively small, thus strengthening overland flow and slope erosion. These effects contribute to collapsing gully formation.

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Table 1 Soil properties at the ridge, slope, and valley of collapsing gully region. Values are average ± standard deviation, based on three replicates.

Sites	Depth	Sand	Silt	Clay	Bulk density	Total porosity	Capillary porosity	Non-capillary porosity	Saturated soil moisture	Field water capacity	Aggregate weight percentage	MWD
Ridge	0-20 cm	367.7$±75.5$a$	312.3±19.8	320.0±57.4a	1.49±0.04a	40.48±1.48a	37.99±2.56a	1.65±0.06a	27.24±1.53a			

MWD: mean weight diameter of aggregates; W: weight; DW: dry weight. At the same depths, sites with different lowercase letters indicate significant differences ($p < 0.05$), while the same lowercase letter indicates no significant differences ($p > 0.05$). At the same sites, layers of different depth with different capital letters indicate significant differences ($p < 0.05$), while the same capital letter indicates no significant differences ($p > 0.05$).

Table 2 Characteristics of macropores of different stages of the slope. V is the volume of macropores.

<table>
<tr><th>Stages</th><th>Macropore number</th><th>Volume</th><th>Surface</th><th>Macroporosity</th><th>Mean macropore size</th><th>Mean surface</th><th>Connectivity</th></tr>
<tr><td></td><td>Total</td><td>V ≥ 1 mm³</td><td>Total</td><td>V ≥ 1 mm³</td><td>Total</td><td>V ≥ 1 mm³</td><td>Total</td></tr>
<tr><td>Ridge</td><td>1828$±324b|428±75b|7.8±4.4b|7.5±4.3b|2.9±1.2b|2.6±1.1b|0.34±0.19b|0.33±0.19b|16.8±7.4|58.8±18.5|</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>mid-erosion</td><td>erosion|1189±747b|266±188b|3.4±3.2b|3.2±3.1b|1.7±1.4b|1.5±1.3b|0.15±0.14b|0.14±0.14b|10.6±2.9|5.9</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Figure Captions:

Figure 1 (a) Location of soil core sampling sites in Guangdong Province, China, and (b) geomorphic and environmental setting. Shaded provinces in (a) represent main Benggang distribution areas.

Figure 2 Instrument used to push polyvinyl chloride cylinders into the ground. 1 - steel tube, 2 - window, 3 - lifting assembly (vertical hydraulic jack); 4 - sampling tube (PVC cylinder); 5 - log plate; 6 - steel roof; 7 - struts; 8 - ground spear; 81 - ring; 82 - limit part; 83 - crack; 84 - down-warping part; 85 - up-warping part; 9 - level; 10 - steel ring knife; 101 - front blade; 102 - groove.

Figure 3 Image analysis procedures in the study.

Figure 4 Three-dimensional visualization of soil macropore networks in soil columns and soil macroporosity along soil depth at the ridge, slope, and valley. The number after ridge, slope, or valley indicates the replicated column number.

Figure 5 Macropore numbers along soil depth at (a) ridge, (b) slope, and (c) valley. Black, red, and green solid lines represent macropore numbers of three replicates, with blue solid line showing their mean for each 3 cm depth. Blue short-dash lines indicate number of macropores with equivalent pore diameter > 1 mm.

Figure 6 Distribution of macroporosity along soil column depth at ridge, slope, and valley.

Figure 7 Frequency of equivalent pore diameters of soil columns at different sites.

Note: Figure translations are in progress. See original paper for figures.

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