Disintegration Characteristics of Red Soil

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Red soil, widely distributed in South America, Africa and Southeast Asia (approximately between the 30° S and 30° N latitudes), is formed by the weathering of carbonate or other rocks rich in iron and aluminium oxides in hot and humid climates. The concept of problem soils was first proposed by Wiseman et al. (1988), and it received a rapid response from the international soil community. Problem soils have a wide horizontal distribution range and large longitudinal depth. Such soils represent a relatively difficult research object in the soil mechanics domain, and the related research is thus a key field of geotechnical engineering. At the 2004 International Conference on Progress in Geotechnical Engineering, Evans et al. indicated that red soil, as a type of problem soil, is prone to geological disasters. Red soil is a highly sensitive problem soil in the Earth's crust, owing to its hydrologic characteristics and chemical behaviour, and is known as problematic red soil. In rain or a full water system, under the influence of physical and chemical solutions, the original water-soil composition and structure and micro-cracks in the problem soil are destroyed, and the variation in the physical and chemical fields changes the mechanical properties of the soil, which may result in critical disintegration and other types of deformation and failure. These geological hazards are closely related to the intergranular suction, which, in turn, is related to the mechanical properties of unsaturated red soil, and may threaten building foundations and project construction.

red soil disintegration microstructure intergranular suction

1. Factors Influencing Red Soil Disintegration

The disintegration of rock and soil mass is a common phenomenon in nature, but it was first studied as a scientific topic in 1948. Cassell (1948) studied rock-soil disintegration characteristics and noted that the shear strength of rock-soil materials at the sliding surface was only 1/5–1/26 that of the main body, and this difference could be attributed to the disintegration characteristics of soft rock [1]. Moreover, the magnitude of the wetting-induced disintegration is influenced by the initial water content, dry unit weight, matric suction and vertical stress, among other factors [2][3][4][5][6][7][8]. Soft rock is similar to soil material. Therefore, studies on soft rock can provide certain scientific guidance to explore the disintegration characteristics of red soil.

1.1. Water

The importance of "water" in soil disintegration can be found in the definition of the concept of soil disintegration by many scholars. In fact, the study of water-soil interaction has never stopped in the development of soil mechanics and has always been a hot spot [9][10][11][12][13]. The influence of water on soil disintegration characteristics is mainly based on three aspects: the initial moisture content in undisturbed soil, the dry-wet cycle and the moisture content of remoulded soil.

Initial Moisture Content

Soil initial water content is an important factor affecting soil erosion [14]. The study of the initial water content in soil has important reference significance for soil prevention and control. Liu and Xiong (2002) found that the disintegration process of red sandstone was very significant in the field atmosphere [15]. With the change in temperature and the alternation of the dry-wet cycle, the disintegration of red sandstone could be fully fragmented and gradually formed a relatively stable gradation. The flooded disintegration of dried red sandstone was more significant than that of natural wet red sandstone. Overall, the disintegration of muddy red sandstone is more obvious than that of grainy clastic red sandstone.

Zheng (2005), Cai (2010), Xue and Li (2011), Kong and Chen (2012), Zeng (2012), Jian et al. (2017) and Li et al. (2020) found that the disintegration process of undisturbed granite residual soil could be divided into three stages: slow disintegration in the initial stage, rapid disintegration in the middle stage and slow disintegration in the later stage [16][17][18][19][20][21][22], and the disintegration process was roughly an inclined "*S*"-shaped curve, as shown in **Figure 1**. Under natural conditions, from top to bottom, the soil usually consists of an eluvial layer, a deposition layer, a transition layer and a parent layer. Soil disintegration is usually slow in the eluvial layer and the deposition layer under different initial water content conditions. Conversely, the disintegration occurs rapidly in the transition layer and parent layer. Meanwhile, the gradient of the initial water content has a great influence on the duration for the eluvial and deposition layers in completing disintegration [23]. Generally, the disintegration rate is controlled by the initial water content, the compaction degree and the saturation of red soil, and the initial water content can accelerate the disintegration obviously [20]. Li et al. (2018) and Zhou et al. (2019) indicated that the disintegration was relatively strong when the initial moisture content of soil was low, and the failure phenomenon was more significant [24][25]. The variation trend of the soil disintegration rate in the vertical section could be divided into four types: decreasing type, increasing type, convex peak type and concave valley type [26]. Under non-rainfall conditions, the occurrence of cracks on the slope surface is closely related to its initial water content. When the water content is lower than a certain value, the surface layer begins to produce cracks. With the decrease in water content, the number and width of fractures experience three stages (slow increase, sharp increase and stable development), and finally, this leads to disintegration and slope failure [27].

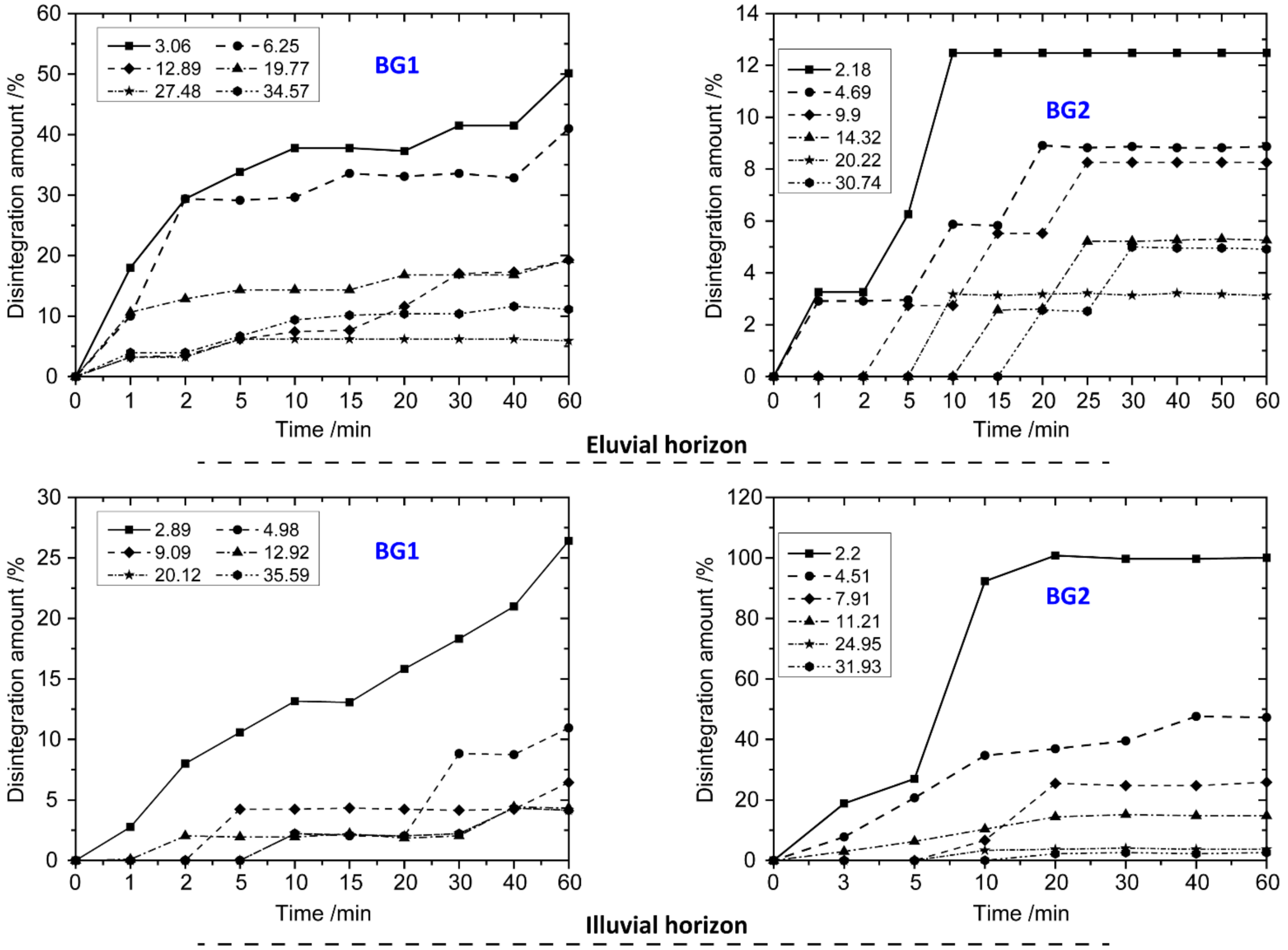


Figure 1. Amount of disintegration under different initial soil moistures at BG1 and BG2 [23].

To sum up, for the influence of the initial moisture content of the undisturbed soil on disintegration, a relatively unified research result is that there are roughly three stages in the disintegration process: slow disintegration in the initial stage, rapid disintegration in the middle stage and slow disintegration in the later stage. The disintegration curve roughly presents a tilt "*S*"-shaped curve. If the initial water content is lower, the disintegration is stronger, the disintegration rate is faster and the destruction phenomenon is more significant.

Wet-Dry Cycle

Due to the influence of seasonal conditions, rainfall, evaporation and changes in the groundwater level, soil is subjected to repeated dry-wet cycles, and the strength and deformation characteristics of soil are often irreversibly destroyed [28]. Tang et al. (2011) and Chen et al. (2011) found that dry samples that experienced dry-wetting cycles could accelerate soil disintegration, and the large number of cracks appearing in the process of dry-wetting cycles was the main reason for soil disintegration in basalt residual soil [29][30]. Zhao et al. (2017) considered more factors such as initial dry density and the number of humidification and dehumidification processes and concluded that clay samples with high initial dry density were more prone to crack than those with low initial dry density under dry-wetting cycle conditions [31]. The wet-dry cycle is the key factor leading to the uneven expansion of red soil in the humidification process. The effect of wet-dry alternation on the disintegration of denatured soil and dry red soil is mainly manifested in two aspects: increasing the maximum disintegration index (the ratio of the total weight of the disintegration soil to the initial weight of the soil) and increasing the disintegration rate (the disintegration amount per unit time) (shown in **Figure 2**). The effect of newly accumulated soil is mainly manifested in shortening the disintegration time [32]. Under a wet–dry cycle, the cohesion of red soil decays obviously in the early stage and then gradually flattens out in the later stage, and finally, it becomes stable. However, the internal friction angle of red soil does not show an obvious change under the wet-dry cycle, which also leads to the cyclic process of cracking, healing and re-cracking for the undisturbed slope [21]. With an increase in rainfall frequency, the cracks develop along the surface of the slope to its depth, and the width and depth of the cracks gradually increase [27]. For research on the characteristics of soil disintegration caused by the wet-dry cycle, the typical results mainly focus on the increase in the disintegration rate of red soil and the shortening of the disintegration process.

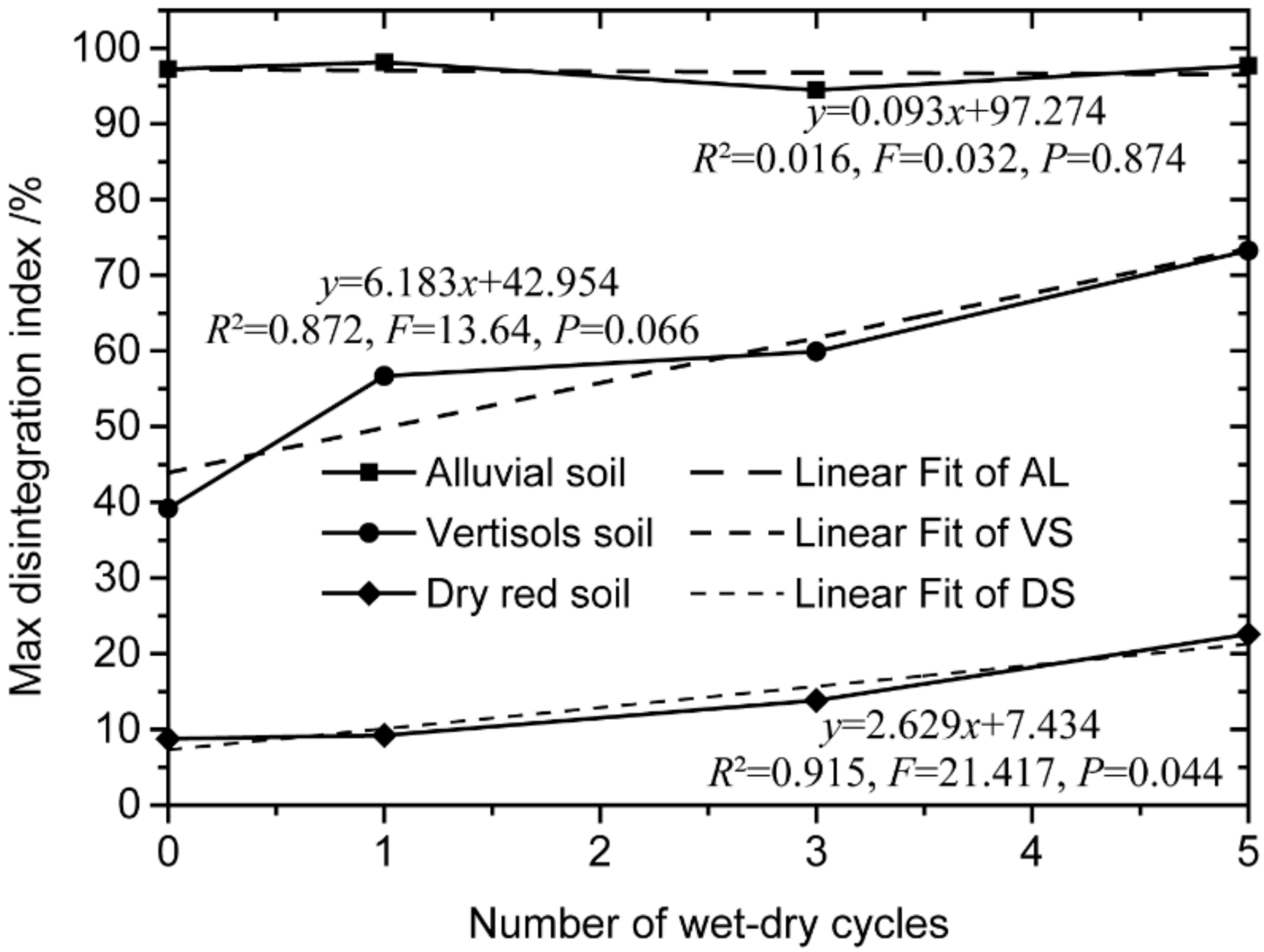


Figure 2. Maximum disintegration index [32].

Moisture Content of Remoulded Soil

Red soil is a kind of special soil; when it touches water under the condition of disturbance, the physical and mechanical properties of the soil will still be quite different. Zheng (2005), Yan et al. (2009), Zeng (2012) and Huang et al. (2017) found that the disintegration rate of remoulded red soil with higher water content is faster than other soils [17][20][33][34]. The disintegration amount decreases with the increase in water content, and when the water content exceeds a certain value, the disintegration of red soil does not occur in a certain period of time [35]. The disintegration process of remoulded soil samples generally goes through two stages: rapid disintegration in the initial stage and slow disintegration in the later stage [17][18][19][20][21]. The disintegration curve is a parabolic curve. The variation of water content directly affects the cohesion, *C*, and the internal friction angle, *φ*, of red soil, and the cohesion is more sensitive than the internal friction angle. Water content is the key factor affecting the disintegration characteristics of red soil, and transient infiltration is the main factor in the initial stage of disintegration [36]. Due to characteristics of water absorption, a sample with low moisture content will present “negative disintegration”, which makes the average disintegration rate lower than the actual situation. The water absorption rate is positively correlated with water temperature and negatively correlated with soil moisture content. When the water content of the sample reaches a certain value, the influence of water absorption on the disintegration of red soil basically disappears [37]. The disintegration curve of red soil exhibits a notable two-stage property (**Figure 3**). In the initial disintegration stage, the curve presents an “S” characteristic, and the initial disintegration rate increases with the decrease in water content [22].

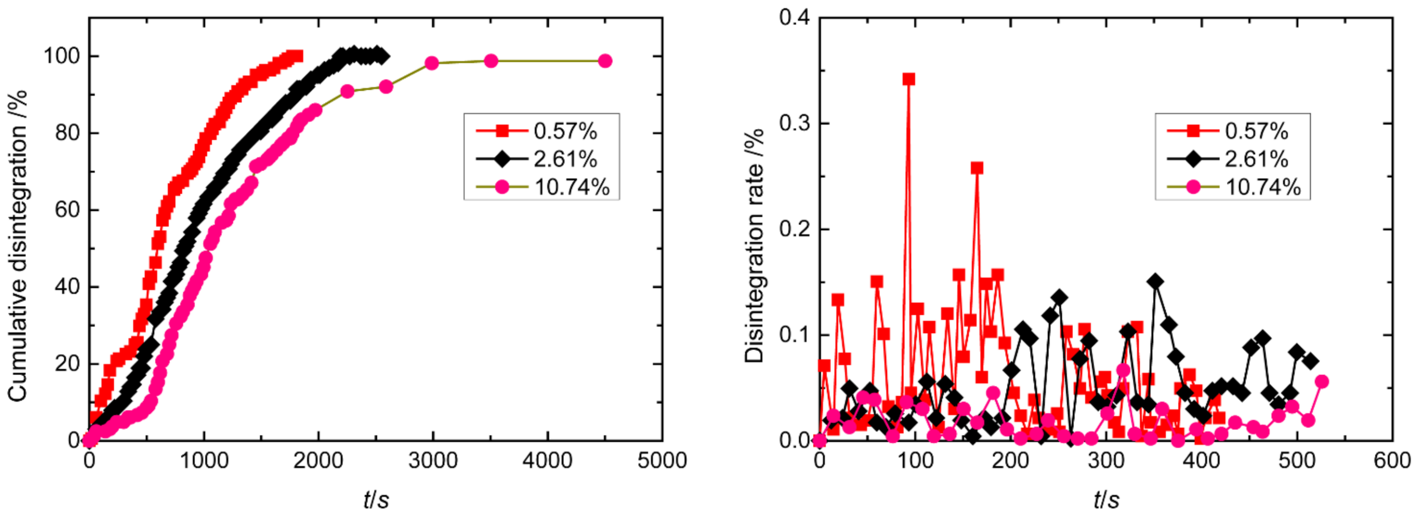


Figure 3. Disintegration curves of granite residual soil [22].

The action mechanism of water is as follows: Due to water sensitivity, the red soil rapidly absorbs water and expands under the action of water, and it produces uneven stress inside and dissolves part of the cementation, leading to disintegration. The typical softening property of red soil when it meets water is the direct factor in the disintegration characteristics.

1.2. Temperature

Gamble (1971) suggested that rock disintegration was caused by water and temperature (with the humidity changes being the main control factors) and highlighted that rock disintegration can be triggered by changes in the rock water content along with other factors, such as physical-chemical reactions between clay minerals and water, the natural water content of weathering rock and grain cementation [38]. However, Yamaguchi et al. (1988) demonstrated that temperature changes did not notably influence rock disintegration in the absence of water migration [39].

In one study, when the temperature increased from 30 °C to 50 °C, amorphous iron gradually crystallised (aged) and formed a firm cemented connection. The reduction in the hydroxylated surface of amorphous iron slowed down the activity of the soil and led to soil disintegration [40]. Tang et al. (2011) indicated that the emergence of a large number of fractures caused by temperature changes was the main reason for the accelerated disintegration of basalt residual soil [29]. At a certain temperature, with an increase in the number of unsaturated-saturated cycles, the damage variable on saturated granite residual soil gradually increases at first and then becomes stable. Zhang and Kong (2016) believed that repeated dry-wet alternation caused by high temperatures and humid climates would destroy particle agglomeration and enhance the dispersion of soil [41]. In their study, the disintegration rate increased with the increase in the number of dry–wet cycles, and the disintegration was dominated by coarse particles and gradually changed to fine particles. The higher the temperature and the more dramatic the climate change, the more significant the effect (**Figure 4**). Guo (2017) found that the mineral activity of red soil was greater at a high temperature, and the disintegration phenomenon was more obvious [42]. The disintegration rate was the slowest when the temperature was 20 °C, and complete disintegration occurred quickly when the temperature was 60 °C. These research results are consistent with those of Tang (2005). Huang et al. (2017) indicated that under different temperature conditions, the damage variable increased after five cycles, which was similar to the change rule of cohesion [34]. However, Zeng et al. (2018) found that the disintegration of red clay increased with the increase in temperature, but the disintegration of red clay was not sensitive to temperature in the natural environment [35].

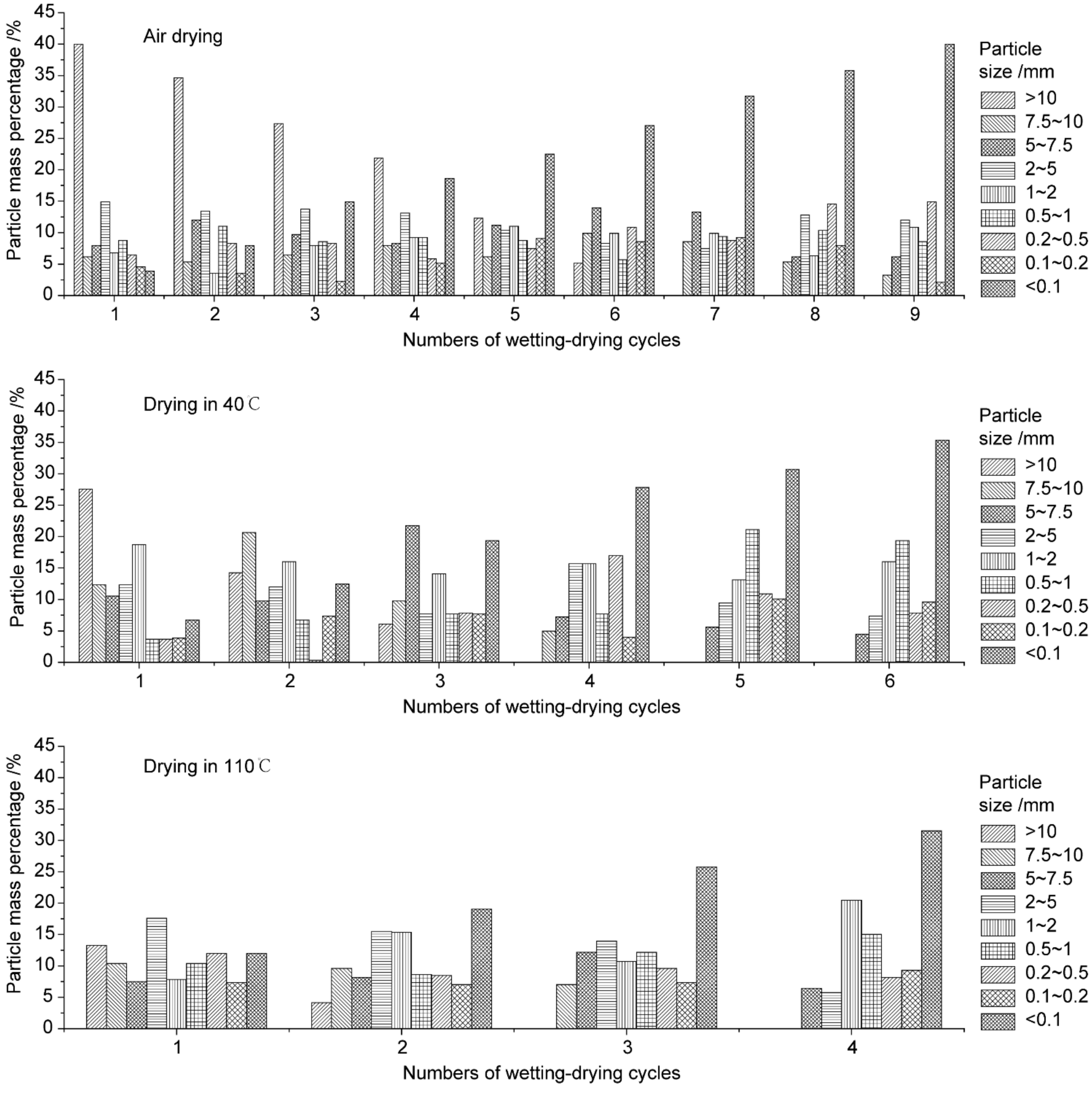


Figure 4. Changes in the particle gradation of the disintegrating substance under different conditions [41].

The mechanism of action of temperature is as follows: the increase or decrease in temperature results in the inconsistent thermal expansion (or cold shrinkage) of mineral particle boundaries in soil due to the different clay mineral compositions. Tensile and compressive stresses are generated between or within mineral particles, resulting in microcracks in the soil. This phenomenon is more obvious when the temperature changes more dramatic. Because the discordant deformation between the mineral particles will be strengthened, so the microcracks in the soil will be more serious and more numerous. Meanwhile, the water on the surface of the soil evaporates faster, but the water inside the soil evaporates more slowly. The uneven distribution of water content forms a hydraulic gradient, resulting in a stress difference between inside and outside, thus forming cracks. The deterioration caused by temperature differences and water migration will enlarge the void between soils and reduce the biting force. Once the temperature is higher, the deterioration is more obvious.

1.3. Pore Air Pressure

Unsaturated soil, as a three-phase composite material widely existing on the surface of the Earth, has far more complex mechanical properties than saturated soil. The difference lies in the interaction of solid, liquid and gas in soil, which leads to suction in the soil pores [43].

Chugh and Missavage (1981) proposed three failure mechanisms of soil disintegration; the first one is tensile stress caused by gas compression in closed pores or fractures [44]. Yan et al. (2009) pointed out that larger external particles were first separated from the soil through water erosion when the sample was immersed in water [33]. Soil pore polarization leads to uneven distribution of potential matrix in soil. When water enters the small pores, it compresses the air gradually, which ultimately reduces the effective stress between the soil particles. Disintegration occurs when the intergranular suction is insufficient to resist the action of air pressure. This stage is the main process of soil disintegration, with the maximum disintegration amount and the highest disintegration rate. Under the action of a wet-dry cycle, the matrix suction increases during dehumidification, and the cementation decomposes and decreases, which causes residual soil failure [45]. Zeng et al. (2018), Xia et al. (2018), Zhang et al. (2018), Zhang and Liu (2018) and Li et al. (2020) indicated that water enters the pores or cracks in an unbalanced way after the soil submerges into the water, leading to the different thickening rates of the intergranular diffusion layer. The repulsion force between the grains exceeds the suction force in different places, resulting in stress concentration and soil disintegration [22][35][46][47][48].

1.4. Mineral Composition

Due to the low cementation content, red soil often shows the unique characteristics of low structural strength, loose structure and high permeability [49][50][51][52][53][54]. The mechanical properties of red soil are very sensitive to changes in mineral composition because the cementation is easily affected by the hot and humid climate of South China. Chugh and Missavage (1981) proposed three destruction mechanisms of soil disintegration, of which the third is the weakening of cementation between mineral particles caused by dissolution and other processes [44]. Huang et al. (2000), Liu and Lu (2000), Tan (2001), Chen et al. (2015) and Zhou and Li (2017) demonstrated the positive effect of free iron oxide on disintegration by using a scanning electron microscope, a micropore tester and other testing equipment [54][55][56][57][58]. When the content of free iron oxide is eliminated, the mechanical properties, especially the disintegration properties, are similar to those of clay [59][60]. Li et al. (2013) tested the chemical composition of red soil and found that the soil was composed of clay, montmorillonite, illite, etc. [61]. The red soil was characterised by microfracture development, a low degree of cement, easy disintegration and so on, as shown in **Figure 5**. Chen et al. (2015) believed that there were water-soluble minerals and kaolinite minerals swelling with water in the granite residual soil, and the existence of these minerals resulted in macroscopic softening and disintegrating characteristics under the action of water [54]. In fact, the disintegration of red soil is not a regular process, which is directly related to the physical properties, especially the content of clay particles. These clay minerals are mainly composed of kaolinite and contain a lot of free iron oxide and aluminium. Gao (1985) found that the colour of red clay was mainly determined by the change of iron oxide content [62]. Free iron oxide is mainly adsorbed on the surface of clay particles in the form of colloids, and a small part is dispersed in the pore solution between particles. The free ferric oxide content and Al-Si ratio of various red soils have a great influence on their chemical composition differences. The free iron oxide in red clay is mainly derived from the weathering of primary iron-bearing minerals and mostly exists in the form of returning ferromagnetic materials. The specific forms are mainly hematite ($\alpha-Fe_2O_3$), goethite ($\alpha-FeOOH$ or $\alpha-Fe_2O_3 \cdot H_2O$) and the amorphous form of iron. In addition, a small part exists in a ferromagnetic form, which is magnetite (Fe_3O_4) and magnetite ($\gamma-Fe_2O_3$) [63]. Zhang and Liu (2018) studied the mineral composition of red soil and found that the particle aggregates formed by clay minerals, such as montmorillonite and illite, made the red soil prone to swelling and dispersed sliding when exposed to water, but the cementing materials in the particle aggregates also improved the strength of the soil [48]. The structural strength of soil mainly comes from the strong bonding force of iron oxide and aluminium, as well as the residual or new chemical bonding force [64]. When the clay content decreases, the disintegration speed increases, which means the disintegration property of soil is enhanced [58][65]. That is to say, the mineral composition and structural characteristics of red soil are the internal causes of disintegration [66].

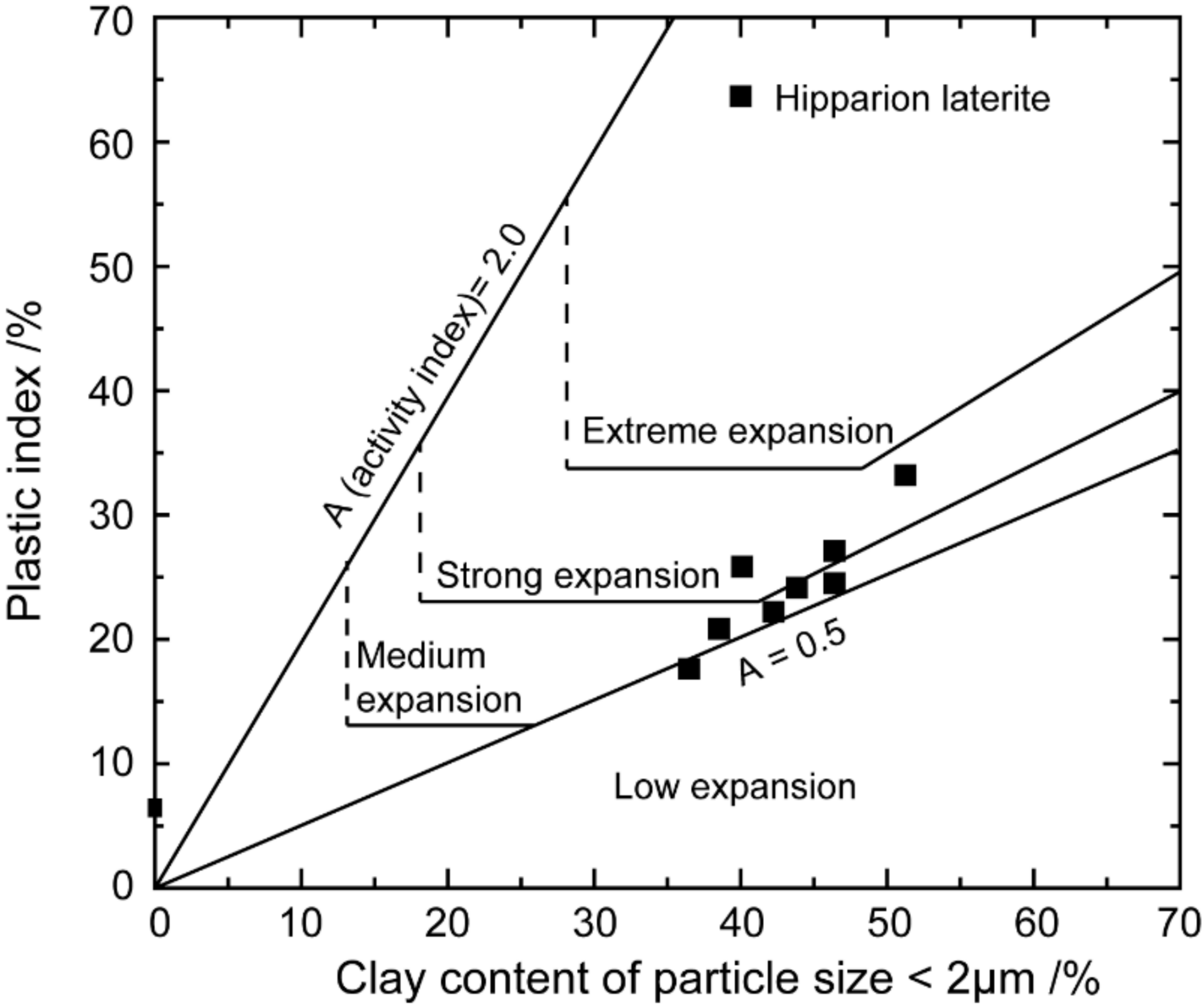


Figure 5. Differentiation diagram for the expansion trend [61].

The action mechanism of the mineral components is as follows: The low cement content of red soil results in low structural strength, strong permeability and a loose structure. In a humid and hot climate, the free iron oxide and alumina are easily damaged and lost. When the soil is disturbed by external environmental factors, the strong cementing force generated by mineral composition and the residual chemical bond force are gradually lost, and finally, the red soil undergoes disintegration.

1.5. Microstructure Change

The soil structure refers to the properties and arrangements of soil particles and pores. Its mechanical properties include the ability of soil to maintain its original structural state without damage. When the structural state is damaged, the mechanical properties will change abruptly [67]. Wu (2006) introduced the disintegration rate index and divided the disintegration process into three stages based on the microstructural characteristics of red soil: the disturbance stage, the structural stage and the solubility stage. The second stage of structural disintegration means that soil disintegration occurs on a large scale, and it is the key stage in the whole process [68]. Meanwhile, the damage model of red soil is divided into two types: strain damage and non-strain damage, in which water softening and mechanical disturbance belong to the non-strain damage. The microstructure of granite residual soil is dominated by clots and flocs (**Figure 6**); micropores with a diameter of less than 1 μm account for more than 70% of the total pores [46][69]. The disintegration rate of red soil is also closely related to soil structure [58]. According to the research results of Zhang et al. (2014) and Xia et al. (2018), particle diameter has a great influence on the disintegration of red soil, and the disintegration rate and amount are proportional to the content of coarse grains [70].

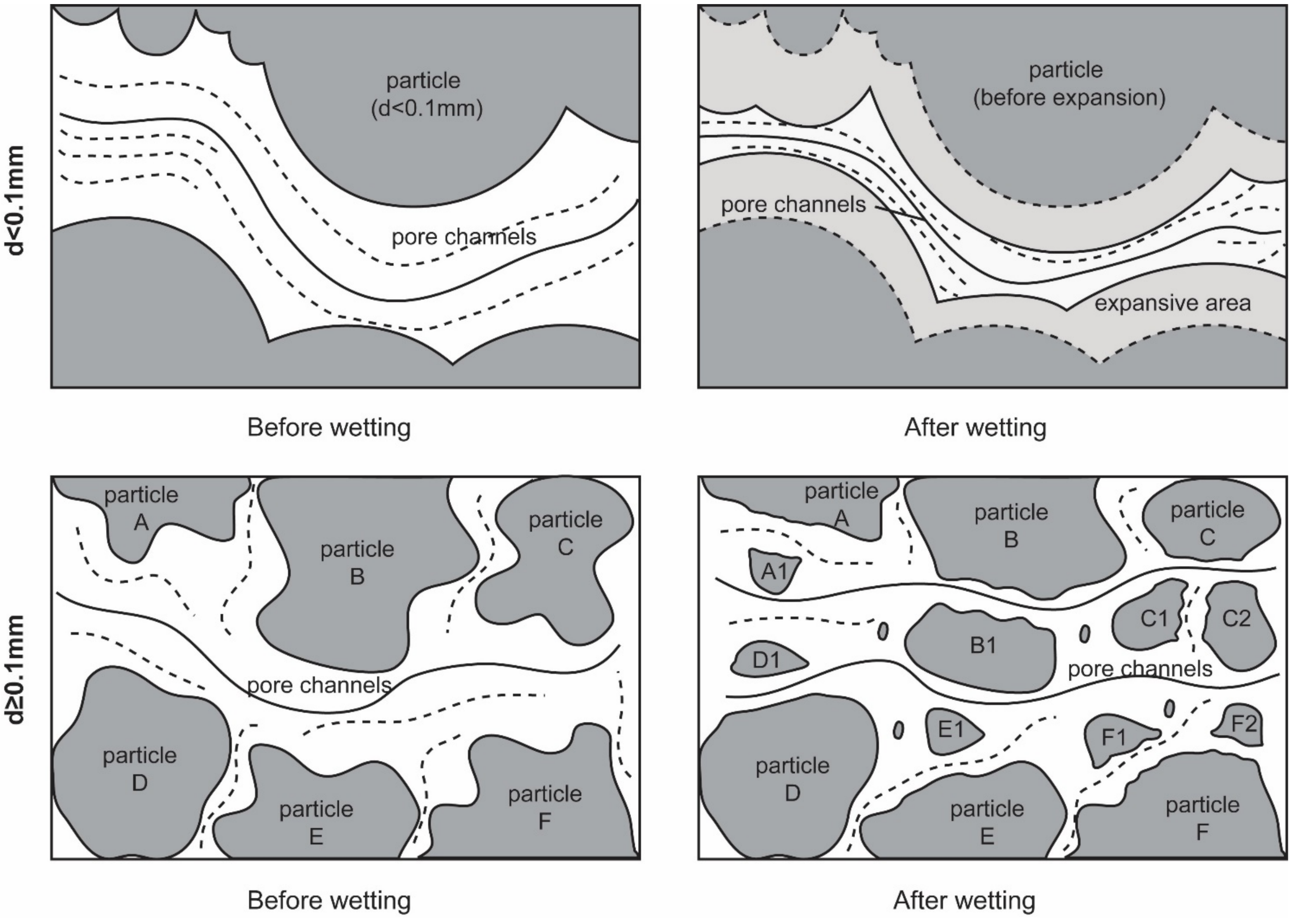


Figure 6. Differentiation diagram of the expansion trend [71].

According to suction theory, the intergranular suction of red soil is mainly composed of structural suction (including intrinsic structural suction and variable structural suction) and absorbed suction [72][73][74]. Red soil is mainly composed of a macroporous structure with coarse grains as a skeleton, and macropores and small pores coexist. When the water content of the sample is small, the variable structure suction and absorbed suction in the small pores are large, while the generalised suction in the large pores is small due to the weak contact between particles. When the water content increases gradually, the fine particles dissolve in the water gradually, and the absorbed suction and variable structure suction at the small pores decrease simultaneously (**Figure 6**). Dissolved small particles continue to precipitate in the macropores, leading to a strengthened particle bond in the macropores [71].

The action mechanism of microstructure is as follows: When the red soil is disturbed by external factors, the equilibrium system composed of cementing materials between soil particles, ions and water molecules is destroyed. The integrity of the original structure cannot be maintained, resulting in the disintegration of the red soil. This effect of microstructure on soil strength is generally reflected by sensitivity.

1.6. pH

Free iron oxides in red soil encase soil particles in an “envelope”, and the adjacent particles are connected in a “bridge” to form larger particle aggregates so that the red soil has a certain “pseudo silty” or “pseudo sandy” quality, which results in the strong sensitivity of red soil to changes in pH [75][76][77]. Tan (2001) pointed out that the chemical composition of water significantly affects soil disintegration, such as the arbitrary discharge of acid and alkali wastewater, which not only causes groundwater pollution but also accelerates soil disintegration [57]. The disintegration rate of an undisturbed soil sample under acid conditions is much higher than under normal conditions. Guo (2017) found that acid solution and natural rainwater could accelerate the disintegration of red soil, and the alkali solution had a certain inhibitory effect on the disintegration [42]. His views are somewhat different from those of Tan (2001), in that an alkaline environment could inhibit the disintegration of red soil. In an acidic environment with the same pH value, the disintegrating amount of red soil is proportional to the soaking time, as shown in **Figure 7**. When the soaking time is the same, the disintegration amount of granite residual soil increases with the decrease in pH value, and the disintegration amount is inversely proportional to the pH [60]. In an acidic environment, an acid solution corrodes several particles and the connections between the particles. The process can be roughly divided into the corrosion stage, the salt-forming stage and the dissolution stage [78]. After these three stages, the strength of red soil decreases obviously, resulting in soil disintegration. The interaction between alkali and red soil can be divided into four types: early hydrolysis, early erosion, middle cementation and late dissolution [79]. The strength varies according to the different processes experienced by the red soil, which may be the reason for the differences between the above research results.

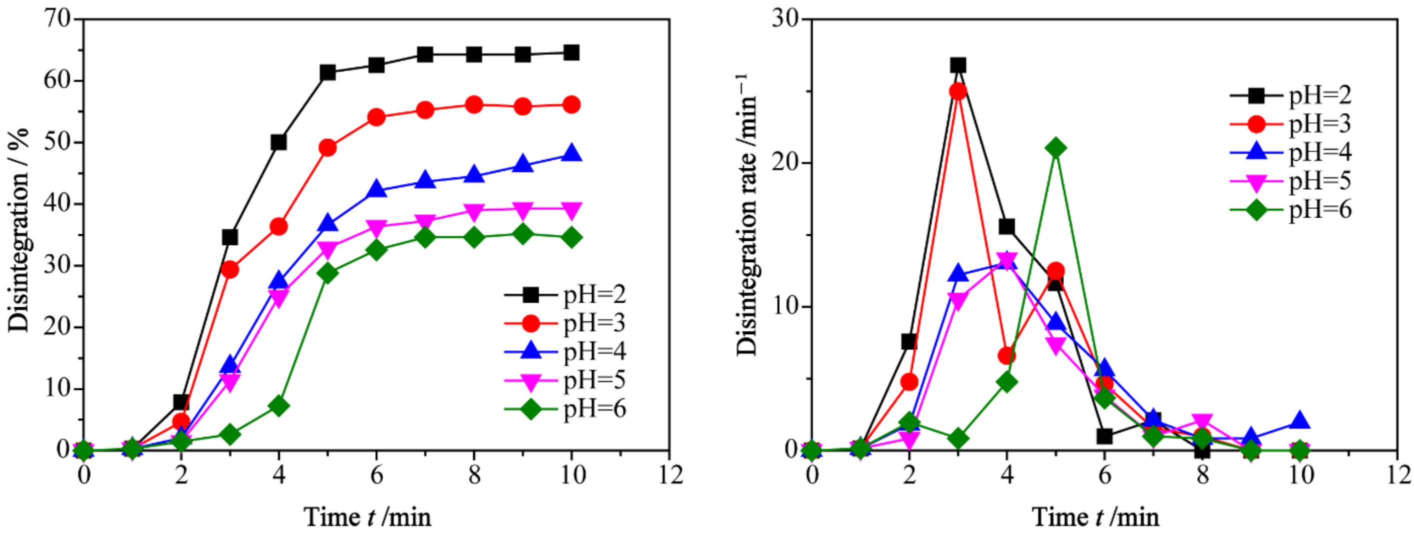


Figure 7. Disintegration curves of samples soaked in different pH solutions for 28 days [60].

The action mechanism of pH is as follows: The strength of granite residual soil is largely affected by the cementation between the soil particles, and the acid and alkaline will dissolve the sesquioxide, calcium, magnesium oxide and other cementing substances in the soil, which will affect the intergranular connection of the soil and destroy the original structure of the soil; the connection between the soil particles will weaken or even disappear. Meanwhile, some insoluble colloidal particles in the soil particles become soluble ions, which also reduce the intergranular bonding force and viscosity and eventually lead to disintegration.

1.7. Multifactor

Red soil is a kind of three-phase, porous, loose medium. There is not only the complex and changeable shrinkage film between the three phases but also the electrochemical and physical interaction between gas, solid and liquid. It is obviously not sufficient to study the disintegration characteristics of such a complex medium structure from a single influencing factor, so it is necessary to consider various influencing factors comprehensively.

Yan et al. (2009) found that water was gradually absorbed into the soil under the action of matric potential [33]. Due to the uneven polarization of the internal microstructure of the soil, a difference in suction pressure between the inside and outside was formed, and the soil suffered structural damage. In the case of unbalanced suction, water first enters the small pores of soil so that the air in the soil is not fully discharged, and the volume of air becomes compressed, leading to an increase in pore pressure. The gas pressure directly promotes the disintegration of soil particles, especially in the unsaturated state, which is more obvious. When the pore pressure is greater than the effective stress, the soil will disintegrate. Chen et al. (2015) indicated that particle size components determine soil porosity and permeability, and they play an important role in the complete disintegration time and disintegration rate of soil [54]. Red soil with fewer clay particles is more permeable, the time for the diffusion layer to reach the maximum thickness is very short and the particle bonding force disappears quickly, so it often disintegrates within a short time. However, soil with more clay particles has poor water permeability, and the duration of the hydration film thickening process is longer. Therefore, the particle bonding force is larger, and the disintegration speed is slower. Guo (2017) analysed the disintegration characteristics of red soil from the perspective of mineral composition and microstructure and found that the alumina and iron oxide in the red soil had a chemical reaction, and the cementing degree of the soil greatly decreased [42]. The expansion of kaolinite leads to an increase in pores, which provides favourable conditions for water to enter the soil, resulting in disintegration. From the perspectives of water, mineral composition, microstructure and suction, Wang et al. (2017) and Guo (2019) pointed out that the cohesion between particles is weak and the pore suction inside the soil is large when the soil sample is in an unsaturated state [80][81]. When soil samples are immersed in water, the water moves through the interconnected pores or internal cracks in the soil, and the gas compresses into the water or out of the soil. The cohesive force between the cementation and the particles decreases with the entry of water. Under the action of the cohesive force and the internal gas expansion force, the soil will spall in the form of powder and particles.

The action mechanism of the cross factors is as follows: Usually, red soil is in an unsaturated state, and the internal pores are relatively developed. Due to the influence of the matric potential, its water absorption capacity is strong. Under conditions such as rainfall (water), water gradually intrudes into the soil, dissolves some of the cementation between particles (mineral composition) and compresses the air in the pores to produce pore gas pressure (suction). Due to the effect of the expansive force generated by pore gas pressure and the expansive force generated by mineral composition, the size and order of soil particles (microstructure) change greatly [82]. When water enters unevenly into pores or fissures, the rate of thickening in the intergranular diffusion layer is not uniform, so the repulsive forces exceed the suction in different places between the grains, which causes the soil to disintegrate along the surface where the repulsive forces exceed the maximum suction. When the soil goes through the dry-wet cycle or the action of the acid solution, the soil disintegration phenomenon is more obvious. The factors affecting disintegration can be divided into external inducible factors and internal sensitive factors. The external inducible factors mainly include water, temperature, acid and basicity. The internal sensitive factors mainly include suction, mineral composition and microstructure. Under the combined action of internal and external factors, the soil mass disintegrates. From the perspective of mechanics, the soil is mainly affected by shrinkage film envelopment force, f_1; expansive force, f_2, generated by mineral composition; buoyancy force, f_3; expansive force, f_4, generated by gas pressure; cementation force, f_5; and gravity force, f_6, as shown in **Figure 8**. When $F_1 + F_5 > F_2 + F_3 + F_4 + F_6$, that is, the anti-disintegrating force is greater than the disintegrating force, the soil sample remains intact and does not disintegrate. When $F_1 + F_5 < F_2 + F_3 + F_4 + F_6$, that is, the anti-disintegrating force is less than the disintegrating force, the soil sample maintains integrity and disintegrates [82].

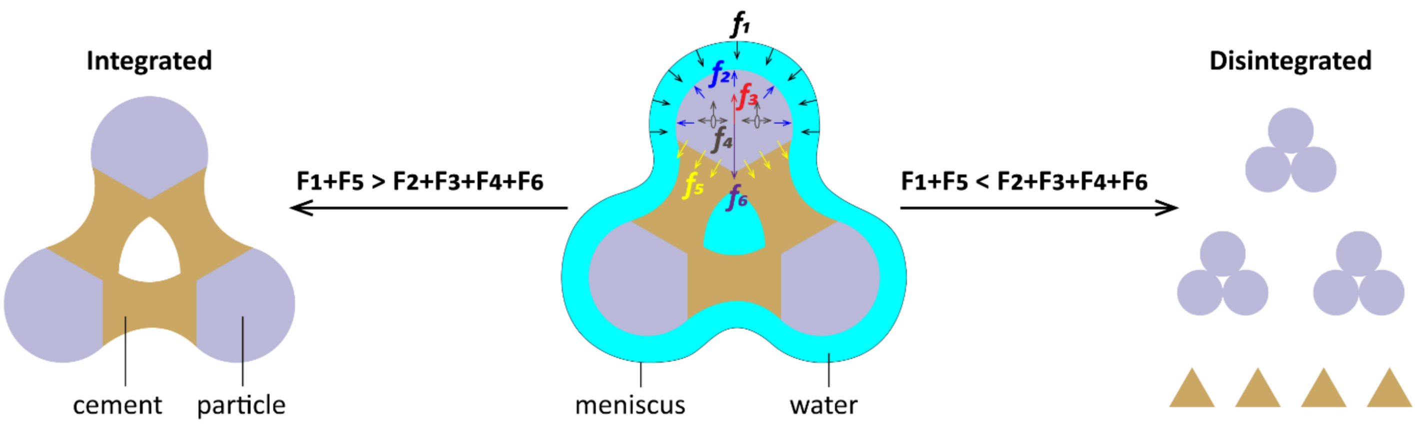


Figure 8. Analysis of disintegration force of soil, illustration of force analysis. Disintegrating force: f_1 is the component of the parcel force of the shrinkage film; f_2 is the component of the swelling force due to mineral composition; f_3 is the component of buoyancy; f_4 is the component of the swelling force due to pore gas; f_5 is the component of the cementing force; and f_6 is the component of gravity. F_1, F_2, F_3, F_4, F_5, and F_6 are, respectively, the resultant forces of f_1, f_2, f_3, f_4, f_5, and f_6 [82].

2. Disintegration Testing Methods

2.1. Laboratory Test

Early studies on soil disintegration were mostly conducted on loess. Due to the collapsibility, loess tends to disintegrate in water, which destroys the integrity and stability of the soil mass. Therefore, Jiang et al. (1995), Wang et al. (2011) and Peng et al. (2017) analysed the influence of the pore characteristics on the soil disintegration of loess with different dry densities and water contents through a self-developed, unsaturated soil disintegrator (**Figure 9**) and established a relationship model between the disintegration rate and effective porosity [83][84][85]. Systematic research on loess disintegration was conducted early, and the research results are relatively mature. Most of the experimental devices used to examine soil disintegration properties are developed based on loess. Red soil has a unique composition and structural characteristics and is widely distributed worldwide, and it is the product of a specific climate, geography and geological environment. Moreover, the engineering geological properties of red soil are different from those of ordinary soils, and it is classified as a regional special soil. The study of red soil as a separate type of soil began in the 1990s, and the research on its disintegration began gradually in the early 21st century. Zhou et al. (2014), Zhao et al. (2017) and Zhou et al. (2019) soaked red soil in water to test the disintegration rate and divided the disintegration process of red soil into three stages: slow disintegration, rapid disintegration and slow disintegration [25][31][86]. Liu et al. (2019) used an analogous sand-bath method to investigate the effects of wet-dry cycles and acid rain on soil disintegration characteristics [87]. In general, disintegration testing is performed using inundation techniques (shown in **Figure 9**); that is, the water’s external inducement factor (which directly influences the pore air pressure, mineral composition and microstructures) is considered, although the temperature is also frequently mentioned.

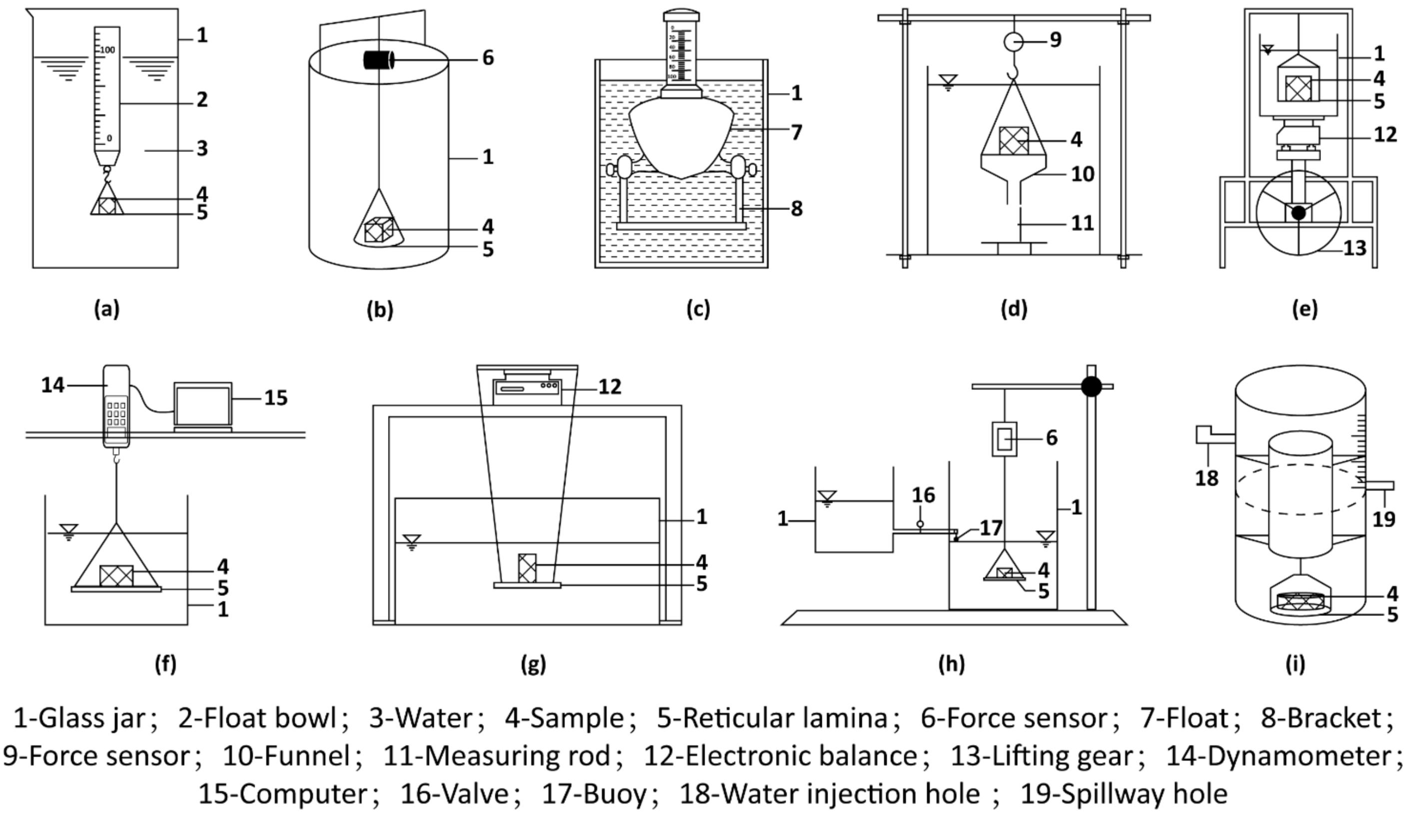
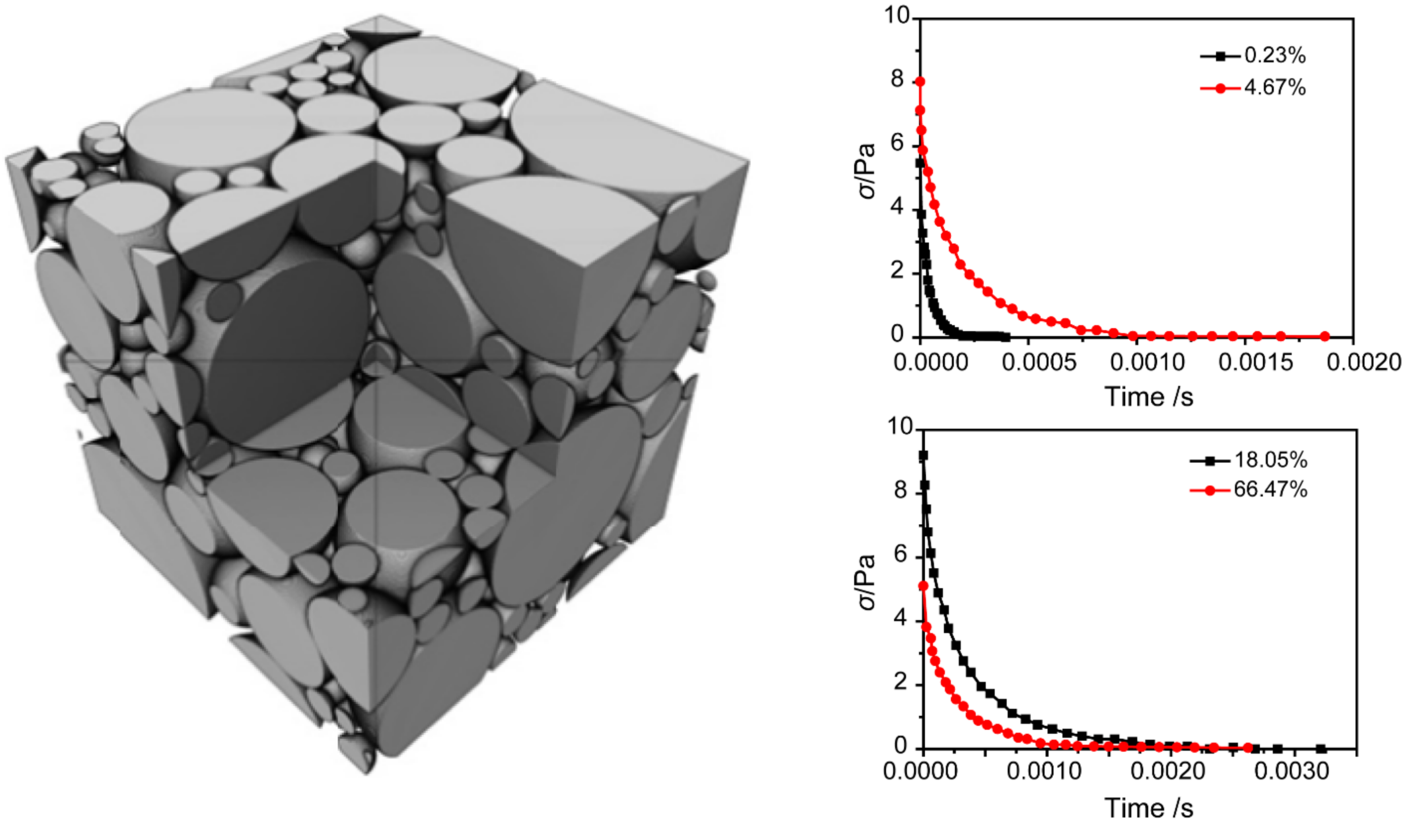


Figure 9. Disintegration testing instruments: Scheme (**a**) [21][22][29][60][83][88][89]; Scheme (**b**) [90]; Scheme (**c**) [64][69][91][92]; Scheme (**d**) [41][93]; Scheme (**e**) [94]; Scheme (**f**) [35]; Scheme (**g**) [25][88]; Scheme (**h**) [95]; Scheme (**i**) [96].

Since Jiang et al. (1995) proposed the buoy-type soil disintegration tester [83] (**Figure 9**a), many researchers have improved the disintegration test device to varying degrees in order to carry out more accurate quantitative research (**Figure 9**b–i). However, the low accuracy led to different research results and even some contradictory conclusions. The experimental study of the soil disintegration effect is still in the primitive stage of discussion. At present, the main quantitative research methods for red soil disintegration are the buoy method (**Figure 9**a,c,i) and the mass method (**Figure 9**b,d–h). For the buoy method, the volume of the displacement liquid decreases with the rise of the buoy, so it is difficult to obtain an accurate scale value of the water level in the test process. There are two main problems: first, the soil disintegration amount needs to be converted by the scale line reading; second, the inner cylinder will float up and down when there is a large of instantaneous disintegration. This makes the readings unstable and prone to errors. For the mass method, the process of placing the sample in water will disturb the water balance and affect the reading precision, which makes it difficult to obtain the initial value.

2.2. Numerical Method

The establishment and development of Euclidean geometry have laid the foundation of all science, and it has become a powerful tool for human exploring the nature [97]. The physical achievements based on Euclidean geometric space continuously promote the development of science, technology and productivity. Since the American mathematician Mandelbrot revealed the relationship between physics and fractal geometry in the early 1980s, fractal geometry has been widely used in the fields of physics, mechanics, biological science, chemistry, geological science, social science, human science and so on [98]. Compared with Euclidean geometry, the advantage of fractal geometry is that it is based on the fractal dimension space, which breaks through the existing mechanics and theories based on Euclidean space and adopts recursive algorithms to describe various shapes and phenomena in nature. The disintegration of remoulded red soil at each moment is a complicated and random phenomenon, which is difficult to describe in traditional Euclidean geometry. Du et al. (2013) used fractal geometric theory to analyse and study the mechanical properties of granular materials in a dumping site and recognised the changing rules of the mechanical properties of such materials from the perspective of a continuously changing fractal dimension [99]. It was pointed out that the inundation and disintegration of granular materials are chronological processes, and the fractal dimension of granular disintegration particle sizes tends toward a stable value gradually with the change in flooding time, which can be used to measure the degree of flooding and disintegration in granular soils. Based on the fractional Brownian motion model in the fractal theory, Li et al. (2015) established a fractal model of the disintegration rate of remoulded red soil samples and determined that the fractal dimension of the disintegration rate was between 1.44 and 1.66 [100]. The fractal dimension will increase with the increase in the moisture content of the samples, and the fractal dimension has a great correlation with the moisture content of the samples. Zhao et al. (2017) studied the crack formation and evolution of red soil using laboratory tests and MATLAB analysis methods, taking into account many factors such as initial dry density, times of humidification and the dehumidification processes [31]. It was pointed out that clay samples with high initial dry density are more prone to cracking than those with low initial dry density under the conditions of a dry-wet cycle. The dry-wet cycle is the key factor leading to the uneven expansion of red soil in the humidification process. Li et al. (2020) preliminarily established an 18-cell method to calculate the unsaturated effective stress under different saturations based on the Pore Algorithm (PM) [22] (**Figure 10**). Combined with the transient infiltration method, the initial disintegration process was approximately simulated, and the disintegration mechanism was analysed from the perspective of unsaturated effective stress.



(a) Schematic of grains

(b) Relationship between σ *and* the infiltration time

Figure 10. Soil disintegration model and calculation results [22].

A large number of laboratory tests show that the disintegration of red soil is not a completely regular process. It is not only related to the complex characteristics of red soil but also a result of the cross-influence of multiple factors and forces; it is full of uncertainty and contingency. Comparatively speaking, the current research on red soil disintegration is still biased to the laboratory test, and numerical research is relatively less.

References

1. Cassell, F.L. Slips in fissured clay. In Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, The Netherlands, 21–30 June 1948.
2. Dudley, J.H. Review of collapsing soils. J. Soil Mech. Found. Eng. 1970, 96, 925–947.
3. Foss, I. Red soil from Kenya as a foundation material. Proceedings of 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, Russia, 15–19 August 1973.

4. Yudhbir, Y. Collapsing behaviour of collapsing soils. Proceeding of the 7th Southeast Asia Geotechnical Conference, Hong Kong, China, 22–26 November 1982.
5. Popescu, M.E. A comparison between the behaviour of swelling and of collapsing soils. Eng. Geol. 1986, 23, 145–163.
6. Lawton, E.C.; Fragaszy, R.J.; Hardcastle, J.H. Collapse of compacted clayey sand. J. Geotech. Eng. 1989, 115, 1252–1267.
7. Tadepalli, R.; Fredlund, D.G. The collapse behaviour of a compacted soil during inundation. Can. Geotech. J. 1991, 28, 477–488.
8. Lawton, E.C.; Fragaszy, R.J.; Hetherington, M.D. Review of wetting induced collapse in compacted soils. J. Geotech. Eng. 1992, 118, 1376–1394.
9. Wang, M. The interaction between water and clay particles in saturated clayey soils. Hydrogeol. Eng. Geol. 1987, 3, 5–16.
10. Wang, Y.; Wang, Y. Effects of soil-water interaction on the flow in soil fissure. Chin. J. Rock Mech. Eng. 1999, 18, 554–557.
11. Wang, Z.; Gong, B.W.; Bao, C.G. Measurement of matrix suction of expansive soil slope in Northern Hubei. Chin. J. Geotech. Eng. 2001, 25, 304–307.
12. Liao, Y.L. Interaction between three phases of cohesive soil and its effects on related indexes. Geotech. Investig. Surv. 2001, 6–8.
13. Zhang, X.G.; Wu, H.; Fang, C. Analysis of X-Ray Diffraction on Variation of Soil Ministructure and Interaction Between Groundwater and Soil. J. Guilin Univ. Technol. 2005, 25, 37–40.
14. Hu, G.F.; Wang, J.; Cai, X.F. Advances in the Effects of Initial Water Content on Soil Erosion. Guizhou Agric. Sci. 2013, 41, 100–103.
15. Liu, D.W.; Xiong, C.R. Experimental Study on Properties of Red Sandstone for Road Applications. Cent. South Highw. Eng. 2002, 22, 19–22.
16. Kong, L.W.; Chen, Z.H. Advancement in the techniques for special soils and slopes. China Civ. Eng. J. 2012, 45, 141–159.
17. Zheng, M.Z. Disintegration Behavior of Residual Soil and Nonlinear Time Series Analysis for Its Slope Displacement. Master's Thesis, Fuzhou University, Fuzhou, China, 2005.
18. Cai, X.L. Study on disintegration characteristics of granite residual soil. Water Conserv. Sci. Technol. Econ. 2010, 16, 882–883.
19. Xue, L.; Li, X.H. Study on Disintegrating Property of Granodiorite Residual Soil and Completely Strong Weathered Rock. Subgrade Engineering 2011, 144–147.

20. Zeng, P. A Study Compaction Characteristics and Disintegration Behavior of Granite Residual Soil. Master's Thesis, South China University of Technology, Guangzhou, China, 2012.
21. Jian, W.B.; Hu, H.R.; Luo, Y.H.; Tang, W.Y. Experimental study on deterioration of granitic residual soil strength in wetting-drying cycles. J. Eng. Geol. 2017, 25, 592–597.
22. Li, C.S.; An, R.; Shu, R.J.; Kong, L.W. Initial-disintegration analysis of granite residual soil and approximate simulation of mathematical morphology. Chin. J. Rock Mech. Eng. 2020, 39, 201–210.
23. Liu, D.L.; Zhao, Y.; Ding, S.W.; Deng, Y.S.; Wang, Q.X.; Lv, G.A. Correlation between initial soil moisture content and the characteristics of collapsing gullies in granite regions. Sci. Soil Water Conserv. 2016, 14, 17–22.
24. Li, Z.; Liu, Y.W.; Zhao, J.F. In-door Experiment of Granite Weathered Residual Soil Disintegration at Sea-cliff. Water Power 2018, 44, 107–110.
25. Zhou, C.Y.; Jing, X.D.; Liu, Z. Disintegration characteristics and modification of weathered soil in red beds in Southern China. J. Eng. Geol. 2019, 27, 1253–1261.
26. Wang, Y.F.; Niu, J. Soil Disintegration Rate in the Upper and Middle Reaches of the Yangtze River. J. Yangtze River Entific Res. Inst. 2015, 32, 40–43.
27. Zhu, Z.Y.; He, G.C.; Li, F.X.; Wang, Z. Experimental Investigation on the Failure Mechanism of Red Soil Slope under Cyclic Wetting and Drying. J. Yangtze River Sci. Res. Inst. 2018, 35, 73–77.
28. Zhang, F.Z.; Chen, X.P. Influence of repeated drying and wetting cycles on mechanical behaviors of unsaturated soil. Chin. J. Geotech. Eng. 2010, 32, 41–46.
29. Tang, J.; Yu, P.; Wei, H.Z.; Meng, Q.S. Slaking behaviour of weathered basalt residual soil in Guizhou. J. Eng. Geol. 2011, 19, 778–783.
30. Chen, D.X.; Yang, Y.; Yang, K.; Kang, K.G. Experimental study on strength and water-stable behavior of unsaturated residual soils. In Proceedings of the International Conference on Remote Sensing, Environment and Transportation Engineering, Nanjing, China, 24–26 June 2011.
31. Zhao, G.G.; Huang, Y.; Zhang, J.F.; Cheng, F.Y.; Zhou, Z.W. Investigation on the Development of Cracks of Laterite of Yunnan Under Wetting-drying Cycles. J. Soil Water Conserv. 2017, 31, 157–165.
32. Zhang, S.; Zheng, X.Y.; Xiong, D.H.; Zhang, B.J.; Yang, D.; Guo, M.; Jiao, L. The Influence of Dry-wet Alternation on the Disintegration of Different Types of Soil in Gully Development Region of Dry-hot Valley. J. Soil Water Conserv 2016, 30, 111–121.
33. Yan, B.; Tang, L.S.; Hu, H.; Wang, D.Z.; Lin, G.W. The mechanism of disintegration damage of granite weathered soil. Hydrogeol. Eng. Geol. 2009, 36, 68–70.

34. Huang, Z.P.; Sun, J.L.; Cao, Y.B.; Zeng, H.J. Temperature effect on strength evolution of saturated granite residual soil. Nonferrous Met. (Min. Sect.) 2017, 69, 54–60.

35. Zeng, Q.J.; Liu, B.C.; Zhang, B.H.; Xiong, J.H.; Xiao, S.D. An experimental study of the disintegration characteristics of red clay. Hydrogeol. Eng. Geol. 2018, 45, 99–103.

36. Wang, Y.; Tang, L.S.; Gao, Q.C.; Liao, H.R. Effects of Water-Soil Interaction on Mechanical Strength of Residual Red Clay. Acta Sci. Nat. Univ. Sunyatseni 2007, 46, 128–132.

37. Zhang, B.H.; Xie, Y.H.; Liu, L. Water absorption of red clay and its influence on the slaking test. Soil Eng. Found. 2020, 34, 98–101.

38. GambleGamble, J. Durability-Plasticity Classification of Shales and Other Argillaceous Rocks. Ph.D. Thesis, University of Illinois at Urbana-Champaign, Champaign, IL, USA, 1971.

39. Yamaguchi, H.; Yoshida, K.; Kuroshima, I.; Fukuda, M. Slaking and Shear Properties of Mudstone. Rock Mech. Power Plants 1988, 1, 133–144.

40. Tang, Q.Y. A Study on the Temperature Effect on the Structural Strength of Granite Residual Red Soil. Master's Thesis, Jilin University, Changchun, China, 2005.

41. Zhang, X.W.; Kong, L.W. Experimental investigation on relative contribution of hot and humid weather and heavy rainfall in disintegration of basalt residual soil. Sci. Sin. 2016, 46, 1175–1184.

42. Guo, T. Study on Disintegration Properties and Microstructure of Guilin Red Clay under Different Environmental Conditions. Master's Thesis, Guilin University of Technology, Guilin, China, 2017.

43. Sun, Y.L.; Tang, L.S.; Liu, J. Advances in research on microstructure and intergranular suction of unsaturated soils. Rock Soil Mech. 2020, 41, 1095–1122.

44. Chugh, Y.P.; Missavage, R.A. Effects of moisture on strata control in coal mines. Eng. Geol. 1981, 17, 241–255.

45. An, R.; Kong, L.W.; Li, C.S.; Luo, X.Q. Strength attenuation and microstructure damage of granite residual soils under hot and rainy weather. Chin. J. Rock Mech. Eng. 2020, 39, 1902–1911.

46. Xia, D.; Zhao, B.Q.; Liu, D.X.; Deng, Y.S.; Cheng, H.; Yan, Y.J.; Ding, S.W.; Cai, C.F. Effect of soil moisture on soil disintegration characteristics of different weathering profiles of collapsing gully in the hilly granitic region, South China. PLoS ONE 2018, 13, e0209427.

47. Zhang, X.W.; Kong, L.W.; Li, H.C. Engineering geological properties and micro-mechanism of residual soils derived from mudstone in Harare, Zimbabwe. J. Eng. Geol. 2018, 26, 1424–1432.

48. Zhang, H.Z.; Liu, J.F. Microstructures, Mineral Compositions, and Mechanical Properties of Red-Layers in Southern China. Adv. Mater. Sci. Eng. 2018, 2018, 9601386.

49. Zhang, S.; Tang, H.M. Experimental study of disintegration mechanism for unsaturated granite residual soil. Rock Soil Mech. 2013, 34, 1668–1674.

50. Reginatto, A.R.; Ferrero, J.C. Collapse potential of soils and soil-water chemistry. Int. J. Rock Mech. Min. Sci. Geomech. 1975, 12, 59.

51. Cheng, B.C.; Xu, C.W. Property of the Cementing Material and Its Influence on Mechanical Characteristics for Residual Soil from Granite. Rock Soil Mech. 1986, 7, 64–69.

52. Wang, Q.; Jiang, H.Z.; Tang, D.X. Study on engineering geological properties of granite residual soil in South Fujian. Geol. Fujian 1990, 9, 90–99.

53. Wang, Q.; Tang, D.X.; Zhang, Q.Y.; Zhao, J.Z. A study on the material structure and composition of granite residual soils in the eastern China. J. Chang. Univ. Earth Sci. 1991, 21, 73–81.

54. Chen, Q.; Li, J.; Zhao, L. Experimental Research on Disintegration Characteristics of Weathered Granite in Nanyue Region. Chin. J. Undergr. Space Eng. 2015, 11, 119–124.

55. Huang, Y.; Fu, B.C.; Fu, J.Q.; Li, Q.S. The Section Properties of the Substance Composition of the Basalt Laterite in Kunming Area. J. Kunming Univ. Sci. Technol. 2000, 25, 88–92.

56. Liu, C.W.; Lu, S.L. Research on mechanism of mudstone degradation and softening in water. Rock Soil Mech. 2000, 21, 29–31.

57. Tan, L.R. Discussion on mechanism of disintegration and argillitization of clay-rock. Rock Soil Mech. 2001, 22, 1–5.

58. Zhou, H.Y.; Li, H.X. The Study on Soil Disintegration Characteristics and Its Influence Factors of Collapsing Wall in the Collapsing Hill Erosion Region of Southern China. J. Soil Water Conserv. 2017, 31, 74–79.

59. Wang, J.Z. The dffects of free iron Oxides on the engineering properties of red clay. Chin. J. Geotech. Eng. 1983, 5, 147–156.

60. Jin, X.; Xiong, C.X.; Zhong, F.L. Experimental Study on Disintegration Characteristics of Granite Residual Soil Under Acid Pollution. J. Water Resour. Archit. Eng. 2017, 15, 194–198.

61. Li, B.; Wu, S.R.; Shi, J.S.; Feng, Z. Engineering geological properties and hazard effects of Hipparion laterite in Baoji, Shaanxi Province. Geol. Bull. China 2013, 32, 1918–1924.

62. Gao, G.R. The Microstructures and Engineering Properties of Red Soil in China. J. Geotech. Eng. 1985, 7, 10–21.

63. Feng, J.L.; Zhao, Z.S.; Gao, G.R. An Exploration for Action and Action Mechanisim of Free Ferric Oxide in Laterite. J. Hebei Acad. Sci. 1994, 1, 35–43.

64. Zhang, Z.; Ma, W.; Zhao, S.P.; Feng, W.J.; Wu, J.J.; Xiao, D.H. Morphological characteristics of the disintegration of cryogenic clay loam, natural and air-dried. J. Glaciol. Geocryol. 2014, 36, 118–122.

65. Xu, Q.Y.; Wang, H.; Wu, J. Preliminary research on the factors affecting the disintegration characteristics of soil. J. Eng. Geol. 2016, 24, 855–860.
66. Xu, H.D.; Wu, S.L. Countermeasures for the Prevention and Control of the Disintegration Disaster Caused by the Yuan Baoshan Red Soil in North China. J. China Univ. Min. Technol. 1996, 25, 30–34.
67. Liu, Z.R.; Liu, C.Y.; Liang, B. Soil Mechanics; Tongji University Press: Shanghai, China, 2005.
68. Wu, N.S. A study on calving property and softening damage parameter of GRS. J. Hebei Inst. Archit. Sci. Technol. 2006, 23, 58–62.
69. Zhang, Z.; Ma, W.; Pendin, V.V.; Zhang, Z.Q.; He, R.X. Experimental study of the disintegration characteristics of loam with different moisture content. Hydrogeol. Eng. Geol. 2014, 41, 104–108.
70. Yuan, W.; Gao, D. The geotechnical characteristics of red clay. China Civ. Eng. J. 1983, 18, 71–78.
71. Sun, Y.L.; Tang, L.S. Use of X-ray computed tomography to study structures and particle contacts of granite residual soil. J. Cent. South Univ. 2019, 26, 938–954.
72. Tang, L.S.; Sang, H.T.; Song, J.; Liu, F.T.; Zhang, P.C. Research on soil particle joint function and brittle-elastoplastic cement damage model of unsaturated granite residual soil. Rock Soil Mech. 2000, 34, 2877–2888.
73. Tang, L.S. Structure Suction and Principle of General Effective Stress in Unsaturated Soils. Acta Sci. Nat. Univ. Sunyatsen 2000, 39, 95–100.
74. Tang, L.S. New suggestion on shear strength in unsaturated soil based on suction between grains. Chin. J. Geotech. Eng. 2001, 23, 412–417.
75. Ma, L.; Wang, Q.; Yuan, G.H. Fractal geometry research on the effect of pH on granulometric composition of red soil. Hydrogeol. Eng. Geol. 2007, 2, 41–44.
76. Ma, L.; Wang, Q.; Yuan, G.H. Effect of pH on properties of red soil. J. Harbin Inst. Technol. 2009, 41, 255–258.
77. Auzet, A.; Kirkby, M.J.; Dijk, P.V. Surface characterisation for soil erosion forecasting. Catena 2005, 62, 77–78.
78. Bo, S.Z.; Huang, Y.; Shi, C.X. Variation characteristics of physical properties of acid pollution laterite. Hydrogeol. Eng. Geol. 2012, 39, 111–115.
79. Ren, L.Q. Study on Macro and Micro Characteristics of Alkali-Contaminated Laterite. Master’s Thesis, Kunming University of Science and Technology, Kunming, China, 2014.
80. Wang, Z.K.; Gao, W.Z.; Liu, F. Soil Slaking Studies on Samples from Guilin Karst Terrain. Soil Eng. Found. 2017, 31, 59–62.

81. Guo, Y.F. The anti-disintegration effect of different curing agents on granite residual soil. J. Fujian Agric. For. Univ. 2019, 48, 225–230.
82. Sun, Y.; Liu, Q.; Xu, H.; Wang, Y.; Tang, L. Influences of different modifiers on the disintegration of improved granite residual soil under wet and dry cycles. Int. J. Min. Sci. Technol. 2022, 32, 831–845.
83. Jiang, D.S.; Li, X.H.; Fan, X.K.; Zhang, H.X. Research on the law of soil disintegration rate change an It's effect factors on the loess plateau. Bull. Soil Water Conserv. 1995, 15, 20–27.
84. Wang, J.E.; Xiang, W.; Bi, R.N. Experimental study of influence of matric suction on disintegration of unsaturated remolded loess. Rock Soil Mech. 2011, 32, 3258–3262.
85. Peng, Y.; Zhang, H.Y.; Lin, C.B.; Wang, X.W.; Yang, L. Engineering properties and improvement mechanism of loess soil modified by consolid system. Chin. J. Rock Mech. Eng. 2017, 36, 762–772.
86. Zhou, X.W.; Liu, P.; Lan, Z. Experimental Study on Disintegration Behavior of Granite Residual Soil. In Proceedings of the Geo-hubei International Conference on Sustainable Civil Infrastructure, Yichang, China, 20–22 July 2014.
87. Liu, W.P.; Song, X.Q.; Huang, F.M.; Hu, L.N. Experimental study on the disintegration of granite residual soil under the combined influence of wetting-drying cycles and acid rain. Geomat. Nat. Hazards Risk 2019, 10, 1912–1927.
88. Lan, Z.X. Experimental Study on Disintegration Behavior of Granite Residual Soil. Master's Thesis, South China University of Technology, Guangzhou, China, 2013.
89. Li, C.S.; Kong, L.W.; Shu, R.J.; An, R.; Zhang, X.W. Disintegration characteristics in granite residual soil and their relationship with the collapsing gully in South China. Open Geosci. 2020, 12, 1116–1126.
90. Gu, T.F.; Yuan, L.; Hu, W.; Zhu, L.F.; Wang, X. Experimental research on disintegration of the Heifangtai loess. Hydrogeol. Eng. Geol. 2017, 44, 62–70.
91. Dmitriev, V.V.; Yarg, L.A. Method and Evaluation of Soil Test; Student's Book: Moscow, Russia, 2008. (In Russian)
92. Zhang, Z.; Vadim, P.; Svetlana, N.; Zhang, Z.Q.; Wu, J.J. Disintegration characteristics of a cryolithogenic clay loam with different water content: Moscow covering loam (prQIII), case study. Eng. Geol. 2019, 258, 105159.
93. Tong, D.K.; Feng, D.; Huang, S.Y.; Ji, X.Z. Experimental Investigation of Compacted Soil Disintegration Property. Sci. Technol. Eng. 2018, 18, 129–136.
94. Li, Q.Y.; Wang, Y.L. Experimental study on some geotechnical humidification characteristics. In Proceedings of the National Engineering Geology Congress, Beijing, China, 21 May 1992.

95. Wang, N.Q.; Wang, Q.T.; Xue, Q.; Liu, X.L. Experimental study of static disintegration on unsaturated soil. Appl. Mech. Mater. 2014, 580–583, 68–72.
96. Li, J.C.; Tian, W.P. Experiment of compacted loess disintegration. J. Chongqing Jiaotong Univ. 2005, 24, 74–77.
97. Lozano-Pérez, T. Spatial Planning: A Configuration Space Approach; Springer: New York, NY, USA, 1990.
98. Santaló, L.; Kac, F. Integral Geometry and Geometric Probability; Addison Wesley Publishing Company: Glenview, IL, USA, 1976.
99. Du, J.; Hou, K.P.; Yang, F. Application of fractal geometry to mechanical properties study of granular material. J. Kunming Univ. Sci. Technol. 2013, 38, 30–35.
100. Li, J.; Chen, Q.; Liu, Z.; He, C. Experimental research on disintegration characteristics of weathered granite in Nanyue. J. Hunan Univ. Sci. Technol. 2015, 30, 59–64.