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Experimental study on the moving characteristics of fine grains in wide grading unconsolidated soil under heavy rainfall

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Abstract: The initiation mechanism of debris flow is regarded as the key step in understanding the debris-flow processes of occurrence, development and damage. Moreover, migration, accumulation and blocking effects of fine particles in soil will lead to soil failure and then develop into debris flow. Based on this hypothesis and considering the three factors of slope gradient, rainfall duration and rainfall intensity, 16 flume experiments were designed using the method of orthogonal design and completed in a laboratory. Particle composition changes in slope toe, volumetric water content, fine particle movement characteristics and soil failure mechanism were analyzed and understood as follows: the soil has complex, random and unstable structures, which causes remarkable pore characteristics of poor connectivity, non-uniformity and easy variation. The major factors that influence fine particle migration are rainfall intensity and slope. Rainfall intensity dominates particle movement, whereby high intensity rainfall induces a large number of mass movement and sharp fluctuation, causing more fine particles to accumulate at the steep slope toe. The slope toe plays an important role in water collection and fine particle accumulation. Both fine particle migration and coarse particle movement appears similar fluctuation. Fine particle migration is interrupted in unconnected pores, causing pore blockage and fine particle accumulation, which then leads to the formation of a weak layer and further soil failure or collapses. Fine particle movement also causes debris flow formation in two ways: movement on the soil surface and migration inside the soil. The results verify the hypothesis that the function of fine particle migration in soil failure process is conducive for further understanding the formation mechanism of soil failure and debris flow initiation.

Keywords: Wide grading unconsolidated soil; Fine particle migration; Soil failure; Landslide; Debris flow initiation; Flume test; Heavy rainfall

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Introduction

A debris flow is a moving mass of loose mud, sand, soil, rock, water and air that travels down a slope under the influence of gravity, which often occurs in fragile mountain areas and valley terrains.

Followed by the initial failure of the slope, multi-component, multiphase and multi-media mixing flows formed by the mixture of the loose materials and water flows along the slope or channel under gravity (Jakob et al. 2005). The main factors that trigger debris flow include rainwater, infiltration, erosion by runoff water, and slope instability (Hu et al. 2013). Field observations show that soil with broadly graded sizes (from the boulder with a diameter as large as a few meters to the clay particle with a diameter less than 0.005 mm), unconsolidated and non-uniform pore structures are essential source materials for debris flow, which is usually called wide grading unconsolidated (loose) soil (WGLS) (Guo et al. 2015). Large particles usually form a framework structure, while the small ones form a granular structure and fill the void. Simultaneously, clay particles form a net structure and wrap up the large particles. During rainfall, the soil surface can be easily scoured and fine particles gradually migrate downward with the infiltration process in macro-voids and then accumulate on the slope toe or at the bottom of the channel. A portion of the soil pores blocks the void and seepage paths causing an increase in pore water pressure and a reduction of effective stress, thereafter a slope failure or a debris flow will be caused (Wang and Sassa 2003).

An example is the large debris flow in Wenjia Ravine in 2010, which destroyed 300 buildings and caused 12 deaths, as shown in Figure 1. The site investigation showed that the major source material of the debris flow is WGLS. With the effect of rainfall, the movement of fine particle caused the slope failure and the initiation of debris flow. Therefore, the fine particle movements will be a major factor in triggering debris flow under rainfall.

Many scholars have done research about fine particle influence on slope stability and debris-flow formation Cui (1992a, 1992b) found that fine particles are a major factor in inducing debris flow, as well as building up cusp catastrophe models for debris- flow initiation. Thereafter, researchers of the Jiangjia Ravine debris flow in southwestern China confirmed that fine particles in gravelly soils have great influence on the formation of debris flow (Cui et al. 2005). Xu (2006) noted that fine particles in shallow gravel soil slopes could move and flow among the gravels during long rainfall periods causing an easy collapse to slopes and

Figure 1 Photos of the post debris flow in Wenjia Ravine with WGLS (Wide grading loose soil) in 2010.

blocking or destroying of drainage channels, while perching the water table. Chen et al. (2010a) studied the effect of clay content on the strength of the gravel soil in the debris flow original area. His research showed that a clay content of 5% -10% in gravel soil would affect the strength of the slope and initiate a large-scale debris flow. Chen's results were then verified by the sample of Jiangjia Ravine debris flow, which contains 5% - 18% clay content (Hu et al. 2011; Chen et al. 2010b; Wang et al. 2010). Wang et al. (2010) studied the behavior of gravelly soil on slope stability in Jangjia Ravine. They observed that free particles were detached from bonding state with rainfall infiltration. These particles were then transported through fluid flow and clogged at some pores, which caused a change in pore pressure and permeability (Cui et al. 2014). The same phenomenon had been observed in some big scale debris-flow experiments (Iverson, 1997; Iverson et al. 1997). Wang et al. (2011) then conducted a soil column experiment under a constant head condition on a debris flow source soil in Jangjia Ravine. They concluded that the migration of fine particles in loose gravelly soil would alter the soil structure and permeability, further influence slope stability. Hu et al. (2013) carried out an artificial rainfall experiment in order to model runoff sediment contents. They concluded that the process of fine particles releasing, migration and accumulation increase the slopes instability, then further induced a landslide or debris flow. Wang et al. (2016) carried out flume tests on debris flow caused by artificial rainfall. The experimental results showed that fine particles dispersed and migrated along the water infiltration path, and blocked the pores, decreasing the infiltration capacity. Moreover, Major and Iverson (1999) concluded that fine particles play an important role in the process of landslide transforming to debris flow based on a number of flume tests and the observation of liquidation. Except for model experiments, a numerical method has been used to verify physical mechanisms, such as water film forming by fine particle accumulation in the soil which reduces the soil strength, and leads to soil failure (Lu and Cui, 2010; Lu et al. 2010). Although the simulation fits for sandy soils, it may not be suitable for wide grading soils.

In summary, most researchers are still invested on the actual characteristics and the phenomenon has not been deeply understood. Although past researchers had observed fine particle migration and the blocking effect, they did not pay attention to the migration rate and volumetric water content variation, which is the focus of this paper. In the aspect of fine particles migration measurement, due to the limit in testing instruments, internal migration regulations can be obtained only by particle grading analysis before and after the experiment. Moreover, it is important to divide the coarse and fine particles for quantitative analysis. Kang and Zhang (1980) found that materials less than 2 mm are the main component of the slurry and particles larger than 2 mm are mainly carried by the fluid of debris flow in Jiangjia Ravine. Later, Cui (1992a) defined the critical value of fine and coarse particles as 1 mm, i. e, less than 1 mm being fine particles and larger than 1 mm being coarse particles. Moreover, clay content of (<0.005 mm) which is regarded as fine particles determines the debris flow pattern and characteristics in the field (Chen et al. 2010b). In the debris flow movement model, Takahashi (2007) separated the soil into coarse particles material (>0.3 mm) and fine particles (<0.3 mm) for different transport models. Based on the analysis above, different particle sizes are adopted in studies to reflect the difference between coarse and fine particles. It is known that coarse and fine particle is relative to particle size. Moreover, in terms of specific physical and mechanical characteristics, the specific particle size of 'coarse' or 'fine' still needs to be distinguished. Hence, we take 2 mm as the critical value to distinguish coarse and fine particles mainly considering maximum pore diameter in wide grading unconsolidated soil and maximum particle size for migration in soil pore observed during preliminary experiments.

The migration of fine particles depends mainly on physical properties of soil and water infiltration. In this paper, three major factors, including slope gradient, rainfall duration and rainfall intensity, were considered. During 16 groups of flume tests arranged by orthogonal design method, fine particle variation in different phases was monitored. Moreover, the downslope transporting of fine particles and the effect on debris-flow initiation in WGLS were analyzed according to the data of volumetric water content and grading size analysis.

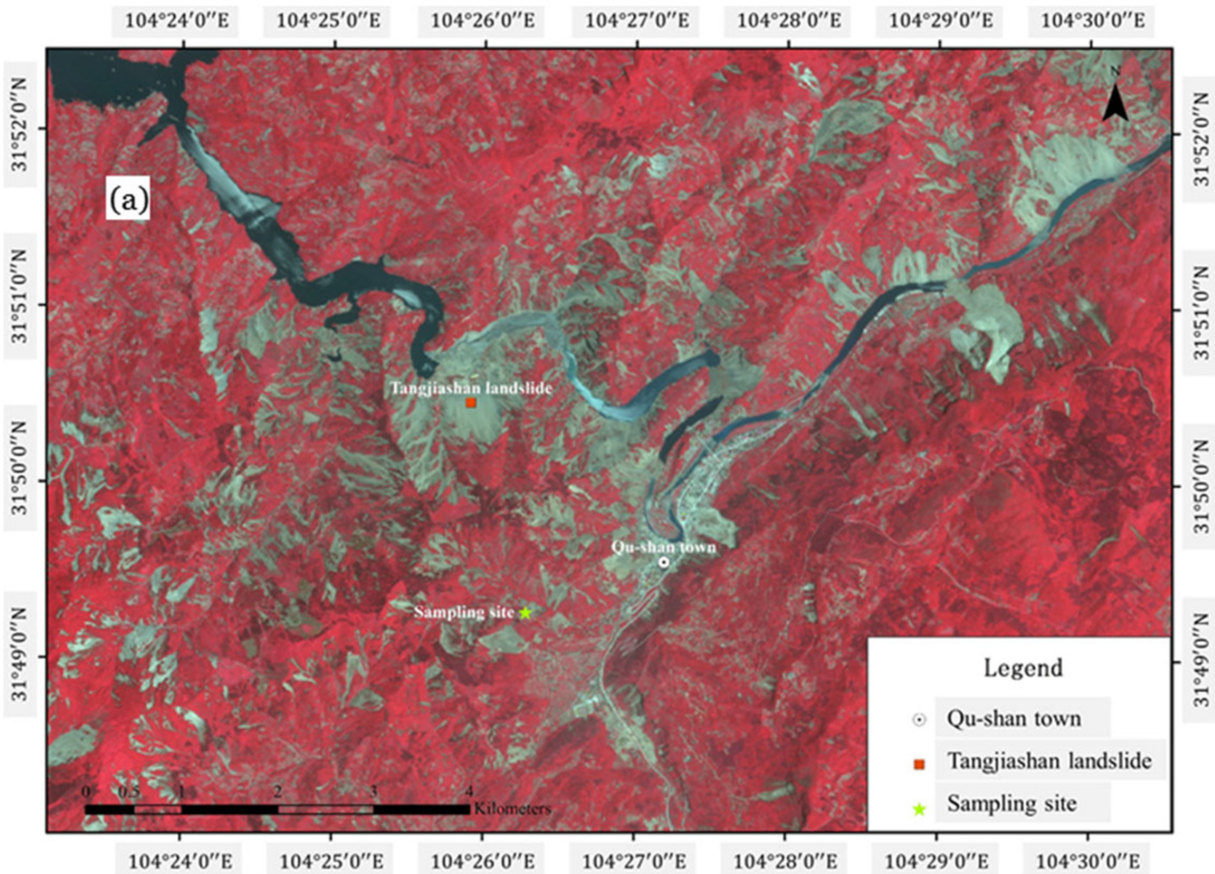
1 Sample Properties

The soil samples were taken on October 2010, from the source area of Weijiagou debris flow in Beichuan, an area heavily hit by the earthquake in 2008. The Weijiagou gully, with a catchment of 0.52 km^2, is located on the right bank of the Jian River and 450 m away from Qushan town, the old country town of Beichuan county, Sichuan province of China (GPS: 104°26'27"E and 31°48'48"N, altitude 650 m). It develops one main gully (length 1.5 km) and two tributaries (the left tributary is 0.155 km long, and the right one is 0.156 km), as shown in Figure 2 a. On September 24th, 2008, a debris flows occurred in Weijiagou and delivered 340,000 m^3 debris outside the catchment, which formed a 144,097 m^2 deposition fan and buried the old county town of Beichuan. The collapsed body triggered by the earthquake is found deposited in the channel. The lithology of the channel is sand slate or shale, which has low strength, loose structure, and poor grading which belongs to coarse grained soil.

Due to the size limitation of the flume and test equipment in the laboratory, particles with large size (more than 60mm in diameter) were eliminated from sampling. The density and particle size distribution in each flume test is kept the same as the original state to make the physical property similar. The basic physical properties of the soil sample in a natural state are illustrated in Table 1. The grading curve in Figure 2 b clearly shows the wide graded features of the soil sample.

2 Experimental Design

The artificial rainfall flume test system is shown in Figure 3, including an adjustable-gradient flume, artificial rainfall equipment, and monitoring devices.



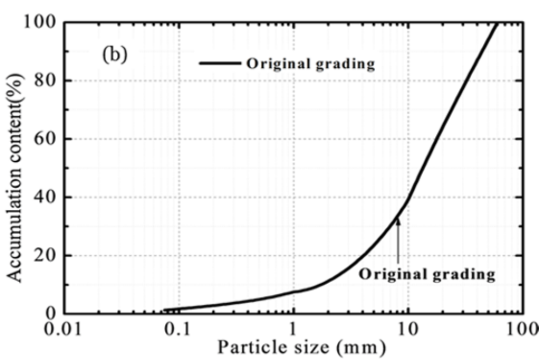


Table 1 The basic physical properties of soil sample taken from source area of debris flow

Sites	ρ_{dry} (g/cm^3)	w_0 (%)	*Gs*	*e*
N31°48'21.08" E104°26'32.03"	1.59	18.9	2.75	0.7

Notes: ρ_{dry}, Dry density; w_0, Initial water content; *Gs*, Specific gravity; *e*, Void ratio

Figure 2 (a) Location of sampling site; (b) The grading size distribution of soil sample.

2.1 Experimental flume

The experiment flume is 300 cm long, 40 cm wide and 40 cm high. The steel frame of the flume is made by an international 5# angle iron (50 mm× 50mm × 5mm) and the left and right sides of the flume are made of toughened glass, and the bottom is made of a non-slip steel plate of thick thread. Flume angle can vary from 10° to 35°.

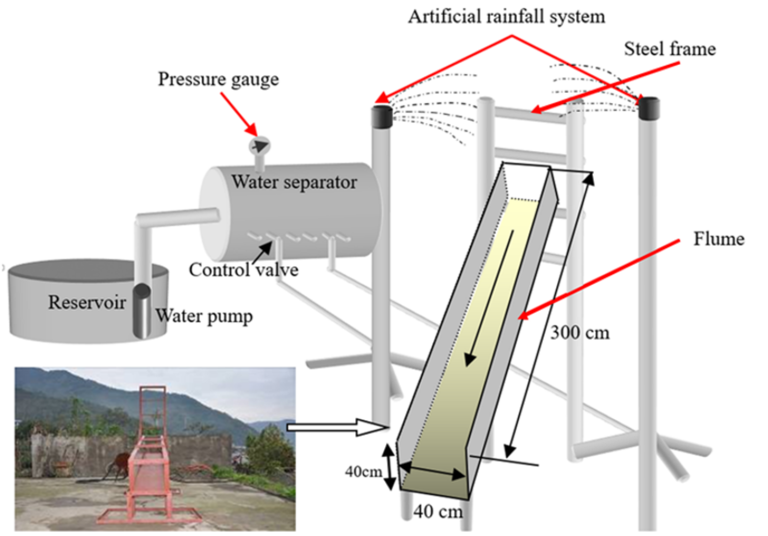


Figure 3 The design drawing of an artificial rainfall flume test system.

2.2 Artificial rainfall equipment

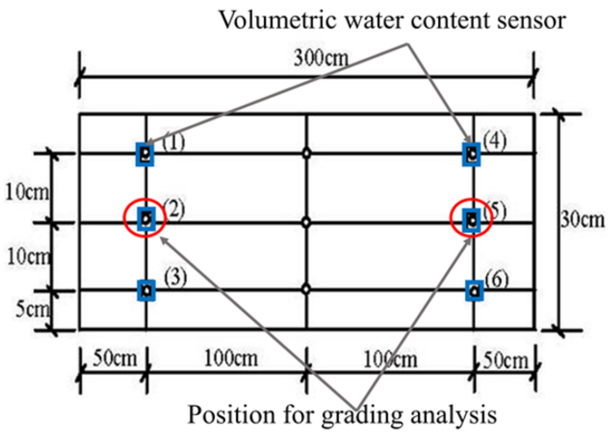
Artificial rainfall equipment consists of rainfall sprinkler head, submersible pump, water distribution tank, side sprinkler head, steel frame as well as pipeline (Figure 3). The rated power of submersible pump is 0.75 kW (highest lift is 18 m, design lift is 13 m, and design flow is 7.8 m^3/h). The water distribution tank includes one pressure gauge, one flushing port and six drainage holes. Valves are used to control the pressure of every drainage hole and produce varying rainfall intensities.

2.3 Monitor equipment

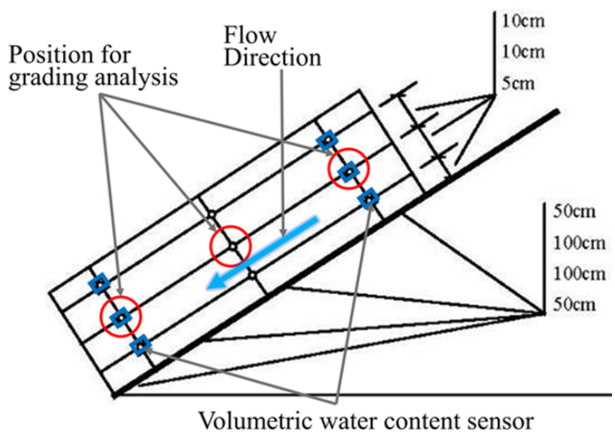
In the experiments, the volumetric water content is real-time measured in the soil. The measuring device, "TDR MiniTRASE Kit" is used in the experiment. The device uses Time Domain Reflectomery (TDR) with 12 data channels to instantaneously measure the volumetric water content of soils. The pore pressure is measured using a US made PSI Pressure System with a full scale from -1.5 to 1.5 kPa, and the static accuracy of ±0.1%. The particles migration process and slope variation characteristics are recorded in real-time via high speed cameras. The soil laid in the flume is approximately 30 cm high, and the detailed arrangement of the sensors is shown in Figure 4 in the cross and longitudinal sections on the slope.

2.4 Experiment program

Three factors influencing fine particles migration are considered in this study: slope gradient, rainfall duration, and rainfall intensity. Each factor is considered with four levels, as shown in Table 2. During the rainy season from June to



(a) Sensor layout at cross section



(b) Sensor layout along longitudinal section

Figure 4 The layout of monitoring sensors.

September in the mountain area of Sichuan, China, the maximum rainfall intensity is always more than 100mm/h (Guo et al. 2015). That is also the main reason for forming geologic hazards such as debris flow and landslide. Moreover, runoff convergence in real status has also influenced the slope stability, but it is difficult to model by short duration test. So we raised the test rainfall intensity based on usual monitoring data at the foot of the mountain, not on the top to compare and analyze this factor (Guo et al. 2016). For these three factors in four levels experiments, a total 64 sets of tests are originally designed. However, only 16 sets of tests are needed (Table 3) for using the orthogonal design principle and the orthogonal table L_{16} (4^5) (Hedayat et al. 1999).

Before the experiment, the flume was first fixed to the steel frame with a planned slope gradient, then the soil sample was laid on the flume bed in batches, and shoveled to the design shape. During the experiment procedure, soil deformation, volumetric water content and the migration features of coarse and fine particles are recorded. In addition, the turbid water flowing out of the flume was measured every 10 min, and the grading size of the soil taken from the slope toe will be analyzed after the test.

Table 2 The factor levels of orthogonal tests

Levels	Factors		
	Rainfall intensity (mm/h)	Rainfall duration (min)	Slope gradient (°)
1	52.86	10	10.74
2	118.85	20	16.74
3	291.72	30	22.94
4	198.47	50	30.56

Table 3 Experimental program using the orthogonal design principle based on three factors and four levels from Table 2

Test No.	Slope gradient (°)	Rainfall duration (min)	Rainfall intensity (mm/h)	Total rainfall (mm)
1	10.74	50	291.72	243.1
2	10.74	10	52.86	8.81
3	10.74	30	118.85	59.43
4	10.74	20	198.47	66.16
5	16.74	20	52.86	17.62
6	16.74	50	118.85	99.04
7	16.74	30	291.72	145.86
8	16.74	10	198.47	33.07
9	22.94	30	52.86	26.43
10	22.94	10	118.85	19.81
11	22.94	20	291.72	97.24
12	22.94	50	198.47	165.39
13	30.56	50	52.86	44.05
14	30.56	20	118.85	39.61
15	30.56	10	291.72	48.62
16	30.56	30	198.47	99.24

3 Analysis on Experiment Process

Based on the experiment observation, the process of the WGLS failure and debris flow initiation under artificial simulation rainfall can be briefly divided into three phases.

The first phase (Figure 5a) is the soil wetting process during water infiltration. In the early stage of this phase, the wetting front in dry soil mass moves downward, and the saturated surface position varies with different infiltration rates and loose soil structures. When rainfall stops, the saturation surface will constantly enlarge with hysteretic effects. During this phase, the soil gradually begins to get wet.

The second phase (Figure 5 b) indicates that, with sustained rainfall and water infiltration, the wetting status of slopes develops from partial-wet to whole-wet. In this phase, a layer of water film can be clearly seen on the interface of the relatively impermeable layer of slope and not only free water but also seepage water exists on the interface. The water film and seepage water separately contribute to the reduction of soil friction.

During the third phase (Figure 5c), with the continuous rainfall, the water content is constantly increasing, which causes soil saturation to finally occur. Furthermore, a small local failure, collapse and slide happen at the front of the soil slope. As the plastic deformation area constantly expands, the scale of slip mass continuously enlarges. In the end, the soil failure occurs totally and develops into debris flow.

4 Analysis of Fine Particle Migration

Under rainfall conditions, fine particles in soil begin to migrate, and some of them may be carried out of the slope by runoff, and others may move and accumulate in the soil with water infiltration. Therefore, considering the two migration ways mentioned above, fine particles migration mechanisms are analyzed as follows.

4.1 Blocking effect by fine particles migration

Fine particle migration in the soil has been well studied. However, due to the limitations in testing instruments, migration patterns are hardly observed. Therefore, particle grading analysis of the sample after the experiment, in our study, can obtain the data to reveal the migration pattern.

A typical phenomenon found many times in the experiments was that the soil would form a layer of water film, and locally saturated layer. Such phenomenon is easier to observe at the slope

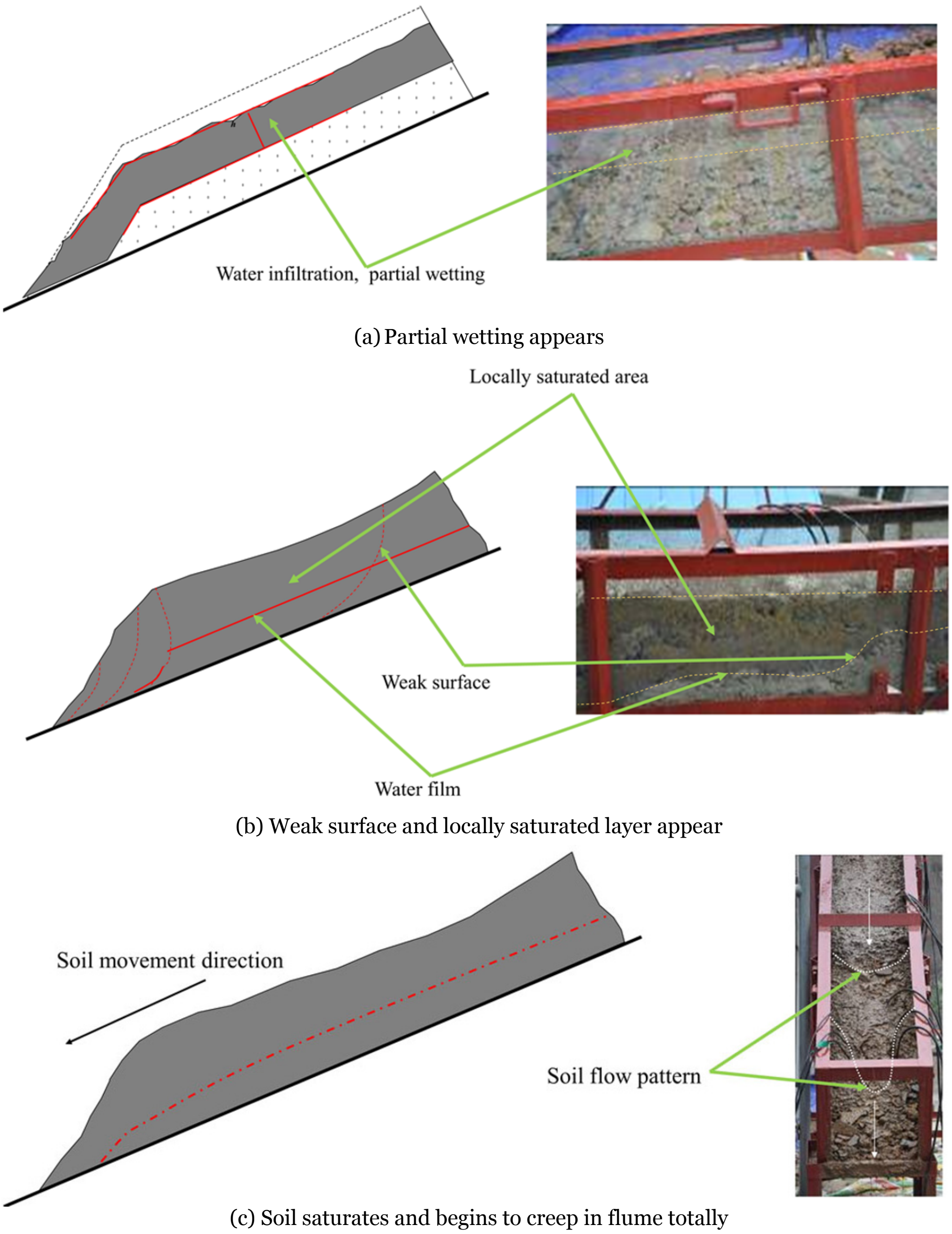


Figure 5 The schematic diagram of WGLS (Wide grading loose soil) failure processes.

toe. In fact, this phenomenon is closely related to the migration of fine particle particles. Primarily, during the rainfall procedure, fine particles in soil are wet and erosion prone. Additionally, water flow in coarse pores of the soil erodes and carries fine particles as infiltration continues. Thereafter, the fine particles will migrate to the deep layer or the toe of slope with the fluid flow through the coarse pores. Due to the non-uniform size and non-connectivity of the pores, some particles may flow through the pores and others may block the pores. As long as blockage appears in a position, the latter particles can change their movement characteristics, and some fine particles will deposit and concentrate on the blocked area. Subsequently, as continuous migration and accumulation of the fine particles occurs, a fine particle layer will be generated that is regarded as a weakest place in the view of soil strength. Along with this procedure, the relatively impermeable layer forms and expands on the weak face and leads to soil failure and debris flow.

Comparing the particle composition at the slope toe before and after the tests (Figure 6), it is found that the content of fine particles after the test is more than that of pre-experiment with the results of the test 1 ~ 4 increasing by 13.10%, 26.11%, 8.4% and 13.33%, and test 5 ~ 8 increasing 1 9.52%, 12.82%, 10.22%, and 17.82%, respectively. The fine particle content increases approximately 8.4% ~ 30.02% through the test, which indicates that the fine particles have migrated in the soil and accumulated at the slope toe. A particle grading analysis of the samples taken from different slope locations (top, middle, and bottom of the slope) after experiments was also conducted. Figure 7 shows grain-size distribution curves of the samples from different positions on the slope at the end of experiments and compares the distinctions of the particle grading characteristics.

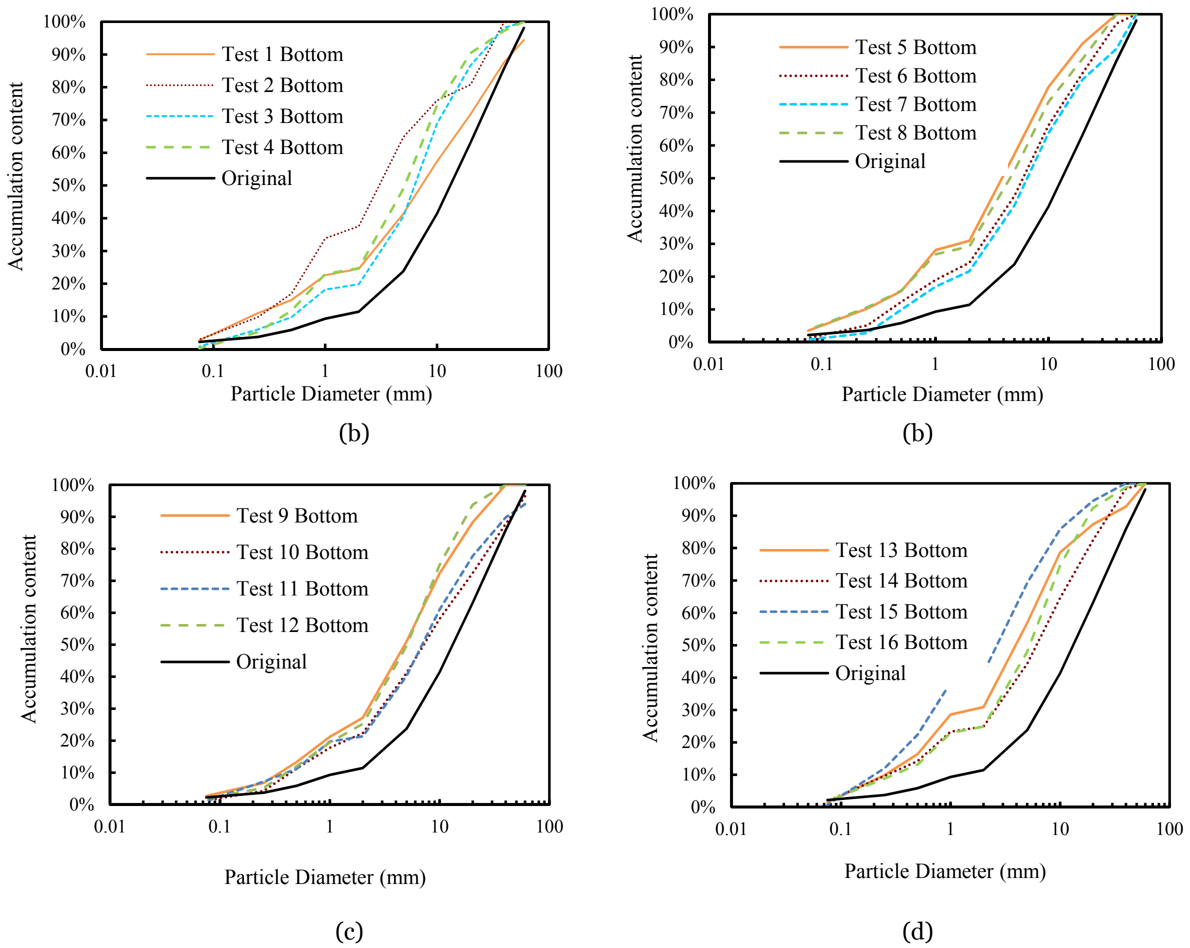


Figure 6 The particle size distribution of the soil at the slope toe pre- and post-experiments from test 1 to test 16.

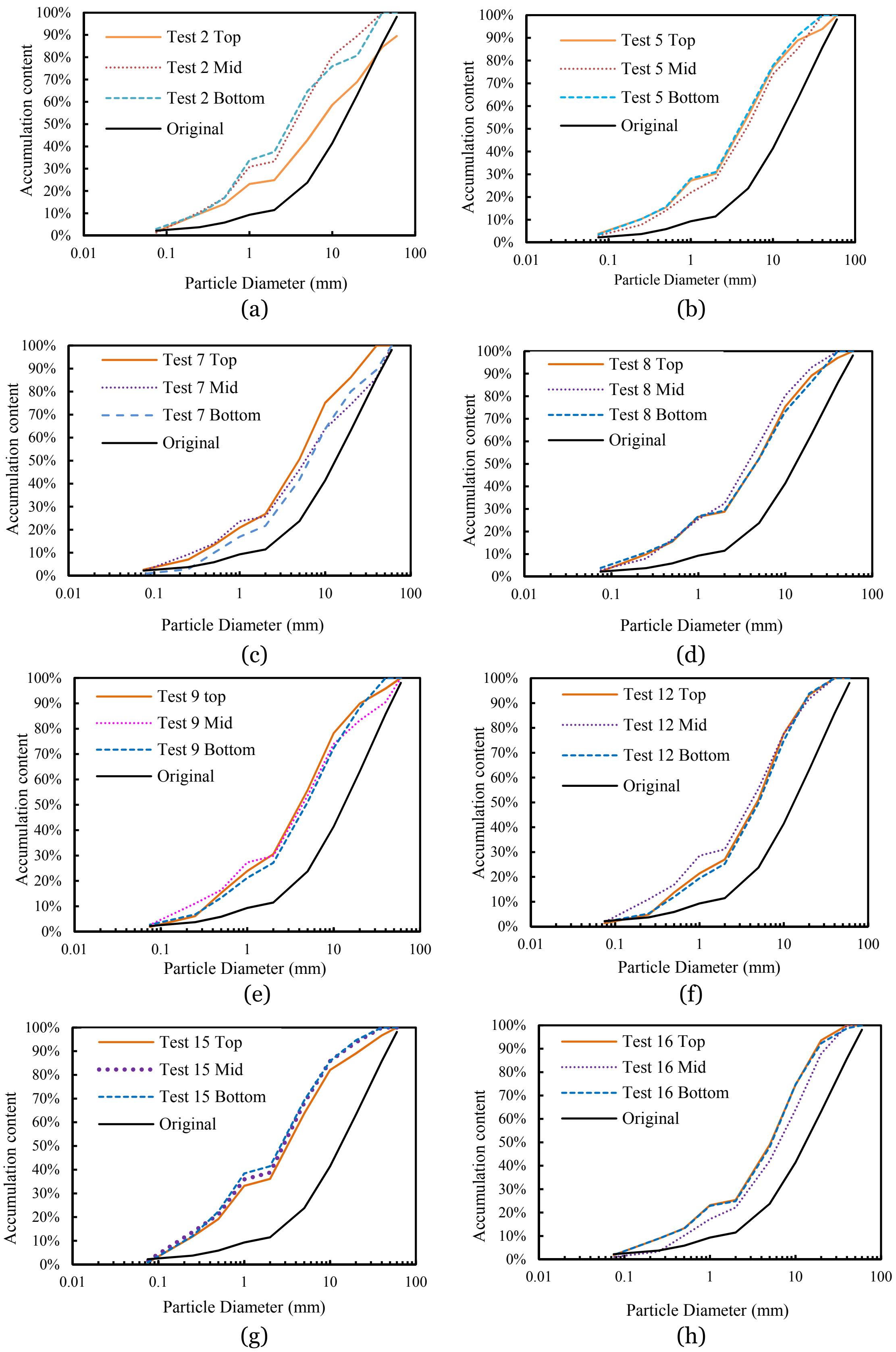


Figure 7 The particle size distribution of the soil samples was taken from different locations of the slope at the end of the test and compared to the pre-test curve.

It is observed from Figure 7 that the fine particle content is higher at the slope toe than at the top and middle, which indicates the direction and process of fine particle migration during heavy rainfall. However, some results in Figure 7 c and e show that the contents of fine particles at the slope toe are smaller than that at the mid and top of the slope. These findings indicate that the normal phenomenon and process, in which the fine particles migrate to and accumulate at the slope toe, could be interfered by subsequent fine particle migration and un-uniformed water flow in the soil. For instance, water flow during heavy rainfall may carry our fine particles from the slope toe and cause a reduction of fine particle content at the slope toe.

Fine particle migration was also analyzed in consideration to different slope angles. The results of particle grading analysis of samples after the experiments from test 3, 8, 9, and 13, designed as different slope angles and almost same total rain fall, were compared as Figure 8. Figure 8 indicates clearly that steep slope results in fine particles accumulation at the slope toe.

4.2 Migration rate of the fine particles

Soil slope containing many fine particles is possible for generating surface runoff and interlamination flow during rainfall. These particles with fine grains are delivered out of the slope toe from surface and internal soil. During the test, the outflow samples were collected every 10 min and then dried and weighed for the subsequent analysis. The variation of fine grain content under different conditions shows obvious fluctuation Figure 9). Taking Figure 9 a as an example, with a slope gradient of 10.74° and rainfall intensity of 291.72 mm/h, fine particles in muddy runoff sharply increase in the initial 0 ~ 20 min, indicating that the situation of the soil fine particles migrating out of the slope with interstitial flow is remarkable; in the 20 ~ 40 min, fine particles content present the downward trend, primarily and then rebound phenomenon. The curve in Figure 9 b shows the procedure of fine particle content as a double repetition from increase to decline. Figure 9 also indicates that the maximum migration rate of fine particles (over 150 g in 10 min) in Figure 9 a is much larger than (less than 18 g) in Figure 9 b.

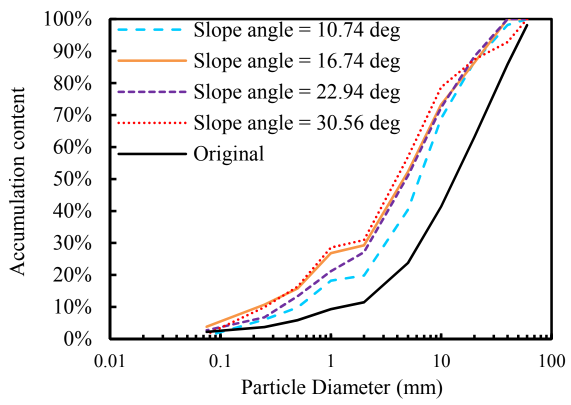
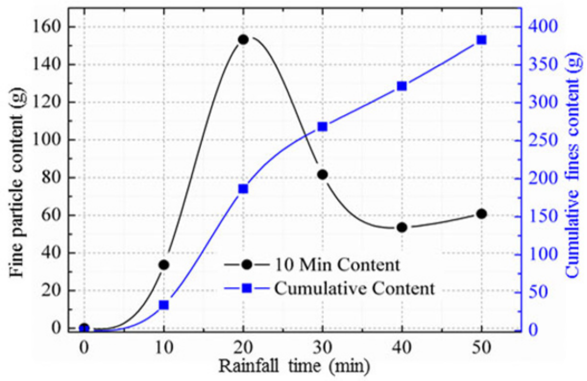
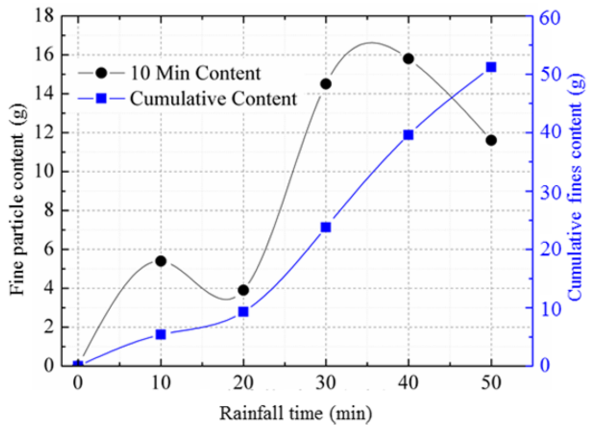


Figure 8 The particle size distribution of the soils at the slope toe at the end of tests with different slope angles.



(a)



(b)

Figure 9 The variation of fine grain content in flume under constant rainfall: (a) Test 1 conditions: rainfall intensity 291.72 mm/h, rainfall duration 50 min and slope 10.74°; (b) Test 13 conditions: rainfall intensity 52.86 mm/h, rainfall duration 50 min and slope 30.56°.

Considering that the steep slope is prone to erosion and fine particle movement, the above results indicate that the migration rate of fine particles increases very sharply under high intensity rainfall conditions and fluctuates within a narrow range and smaller amount under lower rainfall conditions. This means that rainfall intensity dominates fine particle migration rate.

4.3 Variation of volumetric water content

Soil water content reflects on both rainfall infiltration characteristics and soil strength. The variation of volumetric water content during experiments is shown in Figure 10.

Taking test 1 (shown in Figure 10), for example, the water content at the slope toe (sensor 1# at down slope profile) increases sharply initially, reaches a peak of approximately 45% at 10 min, and then remains steady. There is also an apparent lag effect of soil water content from the upper layer to the lower layer. The main reasons for this phenomenon are that sensor 1# is located in the upper surface layer of the down slope and rainfall infiltrating the soil makes the water content increase rapidly at the beginning of rainfall. With continuous rainfall, the soil surface layer becomes saturated. Therefore, the water content appears steady quickly. The volumetric water content variation in the middle layer of the down slope (sensor 2#) is lagging behind the surface layer (sensor 1#) at the same cross section of the slope toe, but it constantly keeps increasing during the experiment which indicates the infiltration process from top to bottom. The water content in the lowest layer (sensor 3#) performs more obvious hysteretic phenomenon than the top soil.

The water content in the profile of the upper slope has the same upward movement trend as the slope toe. However, the water content in surface and middle layers at the slope toe (sensor 1# and 2#) are always higher than those of corresponding positions in the upper slope (sensor 4# and 5#). This result reveals the mechanism that water infiltration processes and infiltration lines develop not only along the vertical direction but also in the inclined plane of slopes from upward to downward.

Therefore, the water content in the surface layer grows rapidly before it reaches a steady trend and maximum value than at other positions.

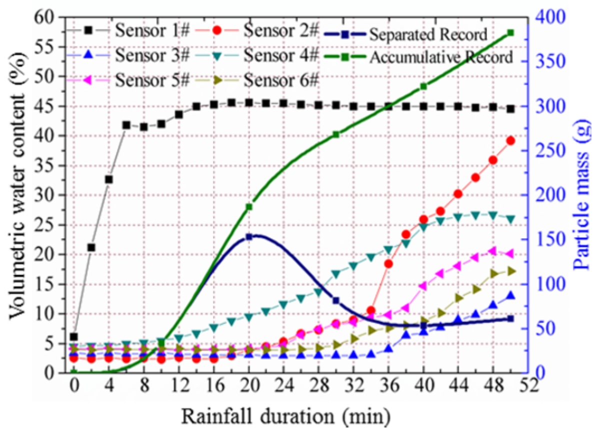


Figure 10 Water content variation in different parts of the slope (Test 1 conditions: rainfall intensity 291.72 mm/h, rainfall duration 50 min and slope 10.74°).

Meanwhile, particle mass carried out by water flow is also shown in Figure 10. Figure 10 shows that fine particle increases with the augment of water content and reaches maximum value at the 20-min mark. Thereafter, the immigrated fine particle diminishes gradually and trends to steady from 40 min. This indicates that fine particle movement not only depends on water flow (water content) but also on the supplement of soil dominated by fine particle content as well as the complex structure of the soil.

Considering the mass balance for a specific unit inside soil, the water content will increase with the fine particle decrease. However, from the view of the fine particle along vertical and slope directions in whole soil layers, the fine particle content variation along the soil profiles is focused for analysis the mechanism of soil failure.

From the above analysis, the rainfall infiltration process develops along both directions in vertical and downward slopes, which indicates that the slope toe plays an important role in water collection and fine particle accumulation, confirming our experimental data.

4.4 Mechanism of fine particle migration

The particle patterns in soil are divided into two types. One is the relative unchanged skeleton composed mainly of coarse grains, which could support the load and transport stress. The other is the mobile part with easy shift characteristics and cannot transport stress. Fine particles mainly exist in the latter pattern and could also agglomerate to form the first pattern. Furthermore, the fine particle movement can be divided into two procedures, they separate first from coarse particles or skeletons and then migrate with water flow into soil pores.

The WGLS has very complex and random structures. Therefore, its pore connectivity is poor, pore sizes are non-uniform and change with the variation of external conditions. The movement characteristic of the fine particles is closely related to the effect of skeleton particles, mobile particles, pore structure and pore water. Pore water causes the mobile particles to steer migration along the flow direction. When mobile particles encounter pores larger than their size, they migrate with water flow from a nearby passageway. Consequently, fine particle migration happens. When some particles come across smaller pores or passages during their movement, they will stop and deposit at the narrowed passages, and then may turn into a part of the skeleton grain due to agglomeration. The agglomerated skeleton grains will not move again until they encounter larger waterpower or external forces leading to be separated.

Meanwhile, under constant rainfall conditions, migration variation of fine particle (<2 mm) mass appears randomly as do fluctuation features. This phenomenon is also verified by the realization of Li (2008, 2012) that, at of same slope gradient and rainfall intensity, the small-scale landslides occur and collapses occur randomly. Therefore, we can regard that every small landslides and collapses are a result of fine particle migration in WGLS. This mechanism can be explained as follows: the increase in internal soil water content causes fine particle migration and then leads to pore enlargement. The enlarged pore is prone to particle migration even providing space for the movement of larger particles. The accumulation effect of fine particle migration changes the structure of skeleton grains, which reduces the skeleton stability and induces a small collapse locally. On the other hand, Soil pores are blocked by migrated fine particles due to poor connectivity and non-uniformity of the soil pore structure. The fine particles accumulate at certain layer and slope toe and form a relatively impermeable layer, which leads to the appearance of saturated layers causing pore water pressure increase and soil strength decrease. Finally, the equilibrium state maintained by occlusion effects and friction of fine and coarse particles which support the particle gravity will be broken. Thereafter, the same effect may induce another landslide and collapse and a similar process may appear continuously. This domino effect would make more fine particles to flow out and lead to a whole slope failure. The process and mechanism of slope failure induced by fine particle migration is shown in Figure 11.

Furthermore, the occurrence of debris flow induced by fine particle migration can be summarized in two ways. First, the continuous movement of fine particle can change the soil structure and reduce skeleton stability while enlarging pore size, which is conducive to more particle movement. As more and more particles participate in the movement, the surface water flow evolves into hyper-concentration flow and further develops into debris flow. Second, due to the blocking effect of fine particles, a relatively impermeable layer generates in the certain layer of the soil and serves as a weak structural plane. A shearing failure will occur in the upper soil of the weak surface during heavy rainfall (Figure 11b). Soon after, the failed soil would be blended in the water flow and then translate into debris flow. In addition to the processes obtained from our laboratory experiments, the above two manners of debris-flow formation can be observed in other fields and can provide new interpretation for the debris-flow initiation process.

4.5 Effect of fine particle migration on soil skeleton

The coarse particle displacement on soil surface in the experiment was estimated by analyzing the experiment video. Figure 12 shows the coarse particle movement/displacement standing for local soil failure and the fine particle mass flowing out of slope. Taking Figure 12(a) for example, the migrated masses, both coarse particles and fine particles, increase sharply in the first 10 min. The video shows that coarse particles mainly slide along the slope surface at the beginning of rainfall infiltration. Therefore, the horizontal displacement is larger than vertical displacement. Thereafter in 10~20 min, with the continuance of fine particles constantly running away and skeleton becoming fragile, local collapse may occur which induces an increase in the vertical displacement of coarse particles and becoming larger than horizontal displacement. Nevertheless, the total displacement appears a downward trend. As fine particles mass reaches peak in 20~30 min, the movement of coarse particles will again increase. By comparing Figure 12 a, b and c, the understanding can be approached as follows.

Rainfall dominate particle movement regardless of fine particles or coarse particles, high intensity rainfall induces large mass movement and sharp fluctuation;

Both fine particles migration and coarse particles movement shows similar fluctuation;

Particle movement increases sharply and quickly drops with a slight fluctuation on gentler slopes with higher rainfall intensity (Figure 12a), and particle movement maintains a slow upward trend with a narrow fluctuation on the steep slope with low intensity rainfall (Figure 12c).

Our experimental results indicate a vital relationship between local soil failure and fine particle migration, which means that fine particles are an important component maintaining whole slope stability. Meanwhile, fine particles (which are mostly clay and fine sand) are prone to liquefy under pore water and move quickly with water. However, coarse particles are always the major component of the soil skeleton, playing a role in transferring stress and supporting the load, and they have stronger resisting shear when coupled with fine particle. Therefore, with the outflow of fine particles, the equilibrium condition of the coarse particles/soil skeleton will become dramatically worse. Additionally, under small disturbance or self-gravity, a large number of coarse particles movement, or soil failure, will occur. Due to heterogeneous grading

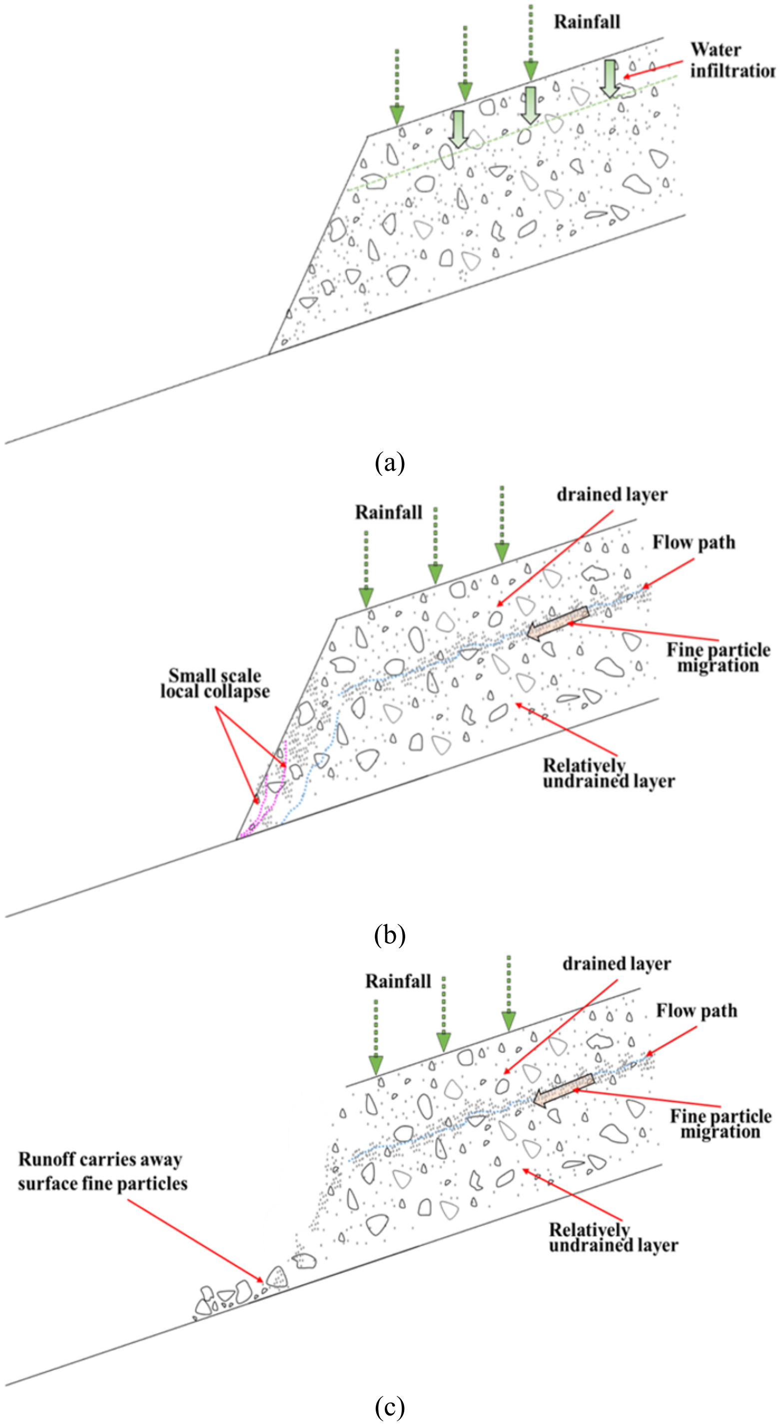


Figure 11 The mechanism of slope failure induced by fine particle migration: (a) Under rainfall, fine particles begin to move. (b) Soil pores are blocked, fine particles accumulated at certain layer and slope toe, relative impermeable layer appears, collapses or failure occur at the slope toe. (c) More fine particles are released, and runoff carries away surface fine particles; coarse particles remain.

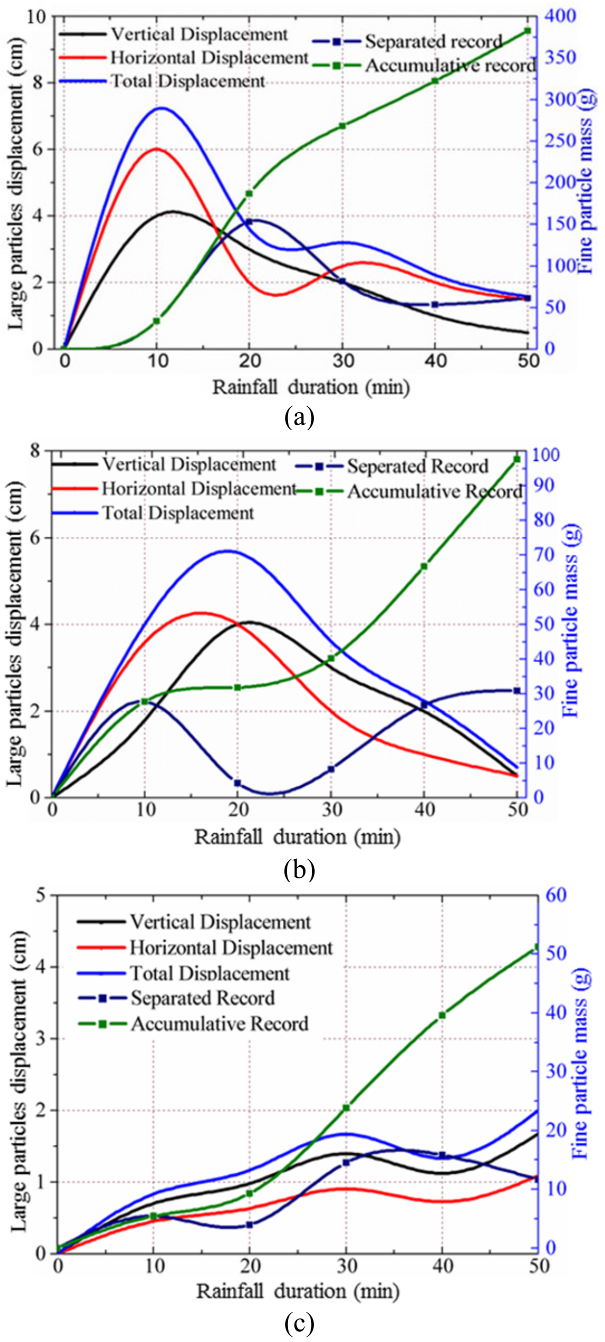


Figure 12 The effect of fine particles migration on large particle displacement and local failure: (a) Test 1 conditions: rainfall intensity 291.72 mm/h, rainfall duration 50 min and slope 10.74°; (b) Test 6 conditions: rainfall intensity 118.85 mm/h, rainfall duration 50 min and slope 16.74°; (c) Test 13 conditions: rainfall intensity 52.86 mm/h, rainfall duration 50 min and slope 30.56°.

and structure, the fluctuation of particle movement and randomness of soil mass destruction has become a significant feature, which is verified by field tests.

6 Conclusion

Sixteen sets of flume tests in total were performed to observe fine particle migration during artificial rainfall. After analyzing the fine particle migration characteristic of wide grading unconsolidated soil (WGLS), the major conclusions are obtained as follows.

(1) WGLS is composed of the soil skeleton (mainly coarse particles) and mobile fine particles. The soil skeleton could support the load and transport stress whereas the mobile part could not. The pores of WGLS have remarkable characteristics of poor connectivity, non-uniformity and easy variation due to its complex, random and unstable structures. Fine particles (<2 mm) can be eroded and carried by water flow of rainfall infiltration in soil pores, which changes the soil structure, including the skeleton and pore structures.

(2) Fine particle content increased on the lower layer and accumulated at the slope toe in our experiments. This result indicates that fine particles migrate vertically and downslope in soil. Rainfall intensity and slope are two major factors for fine particle migration. Rainfall intensity dominates the migration process and rate. The higher the rainfall intensity, the faster fine particles move. Slope plays a secondary role in migration, more fine particles accumulate at steeper slope toe. The variation of fine particle migration rate seems to fluctuate, which reflects the effect of the pore characteristics summed in point (1).

(3) The experimental data can illustrate the mechanism of slope failure induced by fine particle migration. Under rainfall infiltration, fine particles migration has three phases, soil wetting, weak face or saturated layer formation and failure or collapse. As fine particles move with water flow in coarse pores, the poorly connected pores cause an interruption in the migration process and depositing locally, which leads to pore blockage. The blocking effect of fine particles migration induces fine particles accumulation at certain layers and slope toe and forms a relatively impermeable layer. The impermeable layer and slope toe play a role in water influx and fine particles and further develops into a weak surface. Thereafter, collapses or failure occur at the slope toe.

(4) Fine particle migration also contributes to debris flow formation in two ways; the fine particles migrated on the soil surface and inside the soil. Regarding particle migration on soil surface, surface water flow carries particles and evolves into hyper-concentration flow or debris flow. For migration inside soil, fine particle migration forms a weak structural plane in soil and induces shearing failure, and the failed soil translates into debris flow.

The soil composition and dominant structure of wide grading unconsolidated soil play an important role on fine particle migration and slope failure. In the future, soils evolving from different lithology in different climate areas will be adopted to analyze the fine particle migration and assess its effect on the slope failure as well as debris flow initiation.

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