doi:10.11835/j.issn.1671-8224.2014.03.01

To cite this article: ZHOU Jian, ZHOU Yun-hong, LI Ye-xun, WANG Zi-han. Centrifuge model tests of the formation mechanism of coarse sand debris flow [J]. J Chongqing Univ: Eng Ed [ISSN 1671-8224], 2014, 13(3): 77-89.

Centrifuge model tests of the formation mechanism of coarse sand debris flow *

ZHOU Jian 1,2,†, ZHOU Yun-hong 1,2,‡, LI Ye-xun 3, WANG Zi-han 4

1 Department of Geotechnical Engineering, Tongji University, Shanghai 200092, P. R. China
2 Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, P. R. China
3 The Second Engineering Company of CCCC Third Harbor Engineering Co. Ltd., Shanghai 200122, P. R. China
4 School of civil engineering, Hebei University of Technology, Hebei,300401, P. R. China

Received 30 May 2014; received in revised form 11 July 2014

Abstract: Using the self-developed visualization test apparatus, centrifuge model tests at 20g were carried out to research the macro and microscopic formation mechanism of coarse sand debris flows. The formation mode and soil-water interaction mechanism of the debris flows were analyzed from both macroscopic and microscopic points of view respectively using high digital imaging equipment and micro-structure analysis software Geodip. The test results indicate that the forming process of debris flow mainly consists of three stages, namely the infiltration and softening stage, the overall slide stage, and debris flow stage. The essence of simulated coarse sand slope forming debris flow is that local fluidization cause slope to wholly slide. The movement of small particles forms a transient stagnant layer with increasing saturation, causing soil shear strength lost and local fluidization. When the driving force of the saturated soil exceeds the resisting force, debris flow happens on the coarse sand slope immediately.

Keywords: coarse sand debris flow; centrifuge model tests; formation mode; water-soil interaction mechanism

CLC number: P313 Document code: A

1 Introduction

Debris flows are one of the most frequent mass movement processes, which consist of high speed gravity-driven mixtures of soil, rock, and water [1]. Debris flows are common in mountainous and upland areas around the world, usually presenting a serious geological hazard. For example, debris flows in China, British Columbia, Italy, and South East Asia have led to the loss of numerous lives [2-6]. A variety of research efforts have been made to study debris flows. Physical modeling allows boundaries to be defined and
particular perturbations to be input to a model situation, without preconditioning the outcome. The small-scale modelling of debris flows is therefore a useful tool in elucidating particular aspects of their mechanics. Considerable physical model research on debris flows has been conducted, for example, the influence of bed topography, saturation, and density on overall runout behavior \(^7\), and the effect of particle size on runout and erosion by debris flows \(^8\).

There are some drawbacks with the extrapolation of small-scale model behaviors to field-scale debris flow processes. Scaling issues that pertain to laboratory flows over fixed beds have been discussed previously by some researchers such as Iverson \(^9\); they state that by pure virtue of their size, small-scale laboratory flows do not necessarily develop the key dynamics of field-scale debris flows, especially segregation of particle sizes and high mobility. To answer this, many prototype observations and full-scale tests were carried out \(^10\)-\(^12\). Iverson et al. \(^9\) used data from large-scale experiments to assess the entrainment of bed material by debris flows and found that entrainment is accompanied by increased flow momentum and speed only if large positive pore pressures develop in wet bed sediments as the sediments are overridden by debris flows. However, high costs and questionable data restrict their broad application \(^13\).

Centrifuge model tests conducted in a small-scale model have the advantage of reproducing the same stress level with similar deformation and failure mechanisms as those that are presented in a prototype; so they have been used widely in modellings of debris flows. Bowman et al. \(^14\) described a new apparatus to model debris flows in the centrifuge. Milne et al. \(^15\) found that soils with a higher silt fraction can sustain a higher increase in pore water pressure and thus a greater reduction in effective stress before failure is induced via centrifuge tests. Hung et al. \(^16\) explored the scaling of granular flow forces, the consequent bed and wall erosion rates by varying effective gravity from 1g to 100g via centrifuge tests. Most previous research has focused on the macroscopic mechanism of the debris flows as well as the influence factors, while the microscopic mechanism has not been systematically discovered, which still need to be further researched.

This paper seeks to gain an understanding of the micro and macroscopic mechanism of coarse sand debris flows subjected to a continuous rainfall in a 20g centrifuge modeling test. By combining the method of macro and micro analysis, the interaction between soil particles and water are further researched.

2 Centrifuge modelling tests

This study used a geotechnical centrifuge at Tongji University in Shanghai (Fig. 1). It had a 3.0m radius and a capacity of 150g t, and the largest centrifugal acceleration is 200g. At one end of the beam is a basket swinging up during the flight, to which the model is mounted; and at the other end is an adjustable counterweight to balance the entire set-up.

Fig. 1 Geotechnical centrifuge in Tongji University

2.1 Test devices

Centrifuge model test devices of debris flow induced by rainfall mainly included an artificial rainfall system, a model tank and a visual dynamic measurement
2.1.1 Artificial rainfall system

The artificial rainfall system included a uniform atomized sprinkler, a storage tank, a remote pressure regulating system and a remote rainfall control system as shown in Fig. 3. The rainfall device was made up of ten 1.0 mm diameter atomization nozzles arranged into a double-row under a work pressure 0.07 MPa, spraying small and uniform droplets in mist.

2.1.2 Model tank

The model tank was placed in a centrifuge model box with a length of 90 cm, a width of 70 cm, and a depth of 70 cm (Fig. 4). The dimensions of model tank were 25 cm in width and 20 cm in depth. The lengths of the first and second slope base were 35 cm and 33 cm, respectively, and the horizontal plane angles 35° and 15°.

2.1.3 Visual dynamic measurement system

The visual dynamic measurement system was a lighting, digital measurement system used for stereoscopic observation and remote data acquisition system (Fig. 2). Data acquisition system included data acquisition, control and transmission, etc. PDCR81 pore water pressure sensor made by a British company called Druck was used to measure the pore water pressure.

Fig. 2 The sketch map of centrifuge model tests device
2.2 Soil preparation

According to particle size amplification effect of centrifuge model tests, and combined with the geotechnical engineering specification regulations (GB 50021-2001), silt with particle size ranging from 0.05 mm to 0.10 mm was used to simulate coarse sand. The grain composition curve is shown in Fig. 5.

Fig. 3 Remote adjustable artificial rainfall system

Fig. 4 Debris flow model tank

Fig. 5 The grading curve of coarse sand sample, where $x$ is the percentage of particles with a diameter smaller than $d$. 

---

J. Zhou, et al.
Coarse sand debris flow formation

J. Chongqing Univ. Eng. Ed. [ISSN 1671-8224], 2014, 13(3): 77-89
2.3 Test procedure

Step 1: Open the centrifuge host system, oil source system, servo control system, CNC system. Switch on the power and set the centrifuge in the standby state.
Step 2: Open the video monitoring system and data acquisition system, start the centrifuge acceleration to reach 20g, and then consolidate the sample for 20 min.
Step 3: Open the pressure control valve 2 (Fig. 3), and make sure the tank pressure to meet the design rainfall intensity (50 mm/h). Start the cameras for macro observation on the side and at the top to record visual observations. Open the dynamic data acquisition devices to collect testing data such as pore water pressure.
Step 4: Switch on the artificial rainfall system and set the rainfall intensity as 22 mm for 12 h, and then observe and record slope deformation during the test process. Step 5: After the test, close the electromagnetic valve and pressure system to stop the rainfall and data collection, then save the test data and close the centrifuge.

3 Results

3.1 Macro tests

3.1.1 Macro deformation

Fig. 6 depicts the coarse sand slope in the process of forming debris flow during the test, which mainly consists of three stages, namely the infiltration and softening stage, the overall slide stage and debris flow stage.

In the infiltration and softening stage (Fig. 6 (a)), rainwater infiltration line declined slowly due to the small permeability coefficient of the slope. Pore water accumulated in the slope body, resulting in increased pore water pressure and reduced effective stress, as well as reduced soil shear strength; thus the surface subsidence and tensile crack appeared at the back of the slope. As shown in Fig. 6 (b), the overall slide stage began after the saturation line reaching the bottom of the slope, which caused small permeability damage at the slope toe. When the driving force was greater than the resisting force, the overall slope slid suddenly with the sliding speed of the back section greater than the front, which forming a typical slope section of fish. According to the observation shown in Fig. 7 (b), the fluidization already happened at the back of the slope. In the debris flow phase (Fig. 6(c)), loose soil resulted from the slope sliding mixed with rain, together forming a rapid debris flow. As shown in Fig. 7 (c), the rapid flow of water mixed with sand particles was found at the left side of the model tank; whereas the sliding velocity of the right side was relatively small and the soil had been fluidized as well.

---

Fig. 6 Sideways observation pictures at (a) 63 s; (b) 69 s; and (c) 72 s
3.1.2 Displacement field

Fig. 8 describes displacement change map of model slope before forming debris flow. At the beginning of the test, the moisture content of the soil above the saturation line was very high, resulting in a stress layer on slope surface, which made the overall slope consolidated, as shown in Fig. 8(a). With the saturation line downward and the moisture content upward, the total mass of stress layer increased gradually with the slope displacement value as shown in Fig. 8 (b). When it came to 63 s, the displacement value of back slope surface increased gradually and eventually reached 1.2 cm before reaching the limit state, and then the whole slope slid and formed debris flow (Fig. 8 (c)).

3.1.3 Pore water pressure

The positions of observation points in the main body for the model test are shown in Fig. 9, and the pore water pressure changing during the model test process is illustrated in Fig. 10.

Fig. 7 Top observation pictures at (a) 63 s; (b) 69 s; and (c) 72 s

Fig. 8 Displacement field pictures at (a) 21 s; (b) 36 s; and (c) 63 s, unit in cm
Pore water pressure in the model slope grew sustainably during the infiltration and softening stage (0 s to 63 s), mainly because the coarse sand slope was composed of many fine particles (<2.0 mm) and the theoretical coefficient of permeability was 1.9×10^{-2} cm/s, which made the pore water pressure hard to dissipate and thereby increase rapidly once it appeared. We can see that the pore water pressure value at 1°, 2° and 3° observation points constantly grew; whereas that at 4° fluctuated. This phenomenon might have connection with the location of point 4° in the middle of the slope, where a great settlement caused the dissipation of pore water.

In the overall slide stage (63 s to 72 s), pore water pressure of each observation point decreased in different degrees suddenly because of the slide of slope body. We can see that at 68 s, the pore water pressure values at 1°, 2°, 3° and 4° observation points dropped by 9.9 kPa, 5.0 kPa, 4.8 kPa and 4.8 kPa, respectively. In the debris flow phase (after 72 s), the pressure gradually stabilized except that at 1° observation point, where the fluctuation might be induced by the sliding soil from the back section reaching the location of 1° sensor and thus increasing the pore water pressure briefly. The value of pore water pressure at 1°, 2° and 3° was around 0.8 kPa, and that at 4° was −1.0 kPa.

It is shown that pore water pressure has a great effect on the slope deformation and particle movement, which reflects the interaction between water and soil, and the accumulation of pore water plays an important role in
the process of debris flow.

3.2 Micro test results

The observation points 1\textsuperscript{st} and 2\textsuperscript{nd} in slope are chosen for microscopic observation, as shown in Fig. 11. The heights from their locations to the bottom of the slope were 7.5 cm and 2.5 cm, respectively, and the microscopic observation area was 10.0 mm×10.0 mm. A self-developed GEODIP system was used to collect microscopic images. Micro analysis parameters including the long axes orientation and the area of porosity were obtained. The specifications were as described by Zhou Jian\textsuperscript{17}.

![Fig. 11 Microscopic observation points](image)

The silt used to simulate the coarse sand in the centrifuge test was small in size and colorless. Water mixed with red ink was used to simulate artificial rainfall and a thin layer of fine sand including tracer particles was used to facilitate microscopic observation, which would give information about the particle movement of the stimulated coarse sand slope.

3.2.1 Microscopic particle movement

Fig. 12 reflects particle movement of 1\textsuperscript{st} microscopic observation area. In the early stage, the interparticle pore volume was large, so the rain in red color accumulated between the spaces made the slope in red too. Then the tracer particle A was found to move downward at 48 s (Fig. 12 (b)), and the color of the area was light. This is because that the infiltration of pore water led to migration of small size particles, which filled the pore between coarse particles, resulting in settlement and less volume for red rain. Then the tracer particle A continued to move downward at 54 s (Fig. 12 (c)). The direction of pore water seepage was mainly parallel to the bottom to the slope foot, as shown by the red arrows in Fig. 12 (c), and the small particles with weak interlocking migrated with water toward the same direction, forming pore water channels. Moisture content of the slope continued to increase, as well as the particles in small size, which resulted in the gradual disappearance of boundaries between the fine sand layer and the silt layer (Fig. 12 (d)).

3.2.2 Micro fabric analysis

A. Particle long axis orientation

Fig. 13 is the long axis grain rose diagram of 1\# microscopic observation area, which reflects the particles frequency distribution in the direction of the long axis. The polar coordinates represent the relationship between particle numbers and angle. It is shown that the long axis movement experienced three stages, changing from initial uniform distribution to directional distribution, and then back to the uniform distribution.

At the beginning of the test (Fig. 13 (a)), sand particles in the observation area in the long axis direction were in uniform distribution because of the natural rain method. When the time came to 40 s (Fig. 13 (b)), pore water penetrated into the microscopic observation area, and particles moved under the pore water osmosis. Small particles migration and coarse particles skeleton dislocation resulted in the changes of
long axis direction distribution, which was the long axis direction mainly concentrated in the areas from 80° to 90°, and 170° to 180°. After 10 s (Fig. 13 (c)), the long axis directions changed again, and they mainly concentrated in the area between 70° and 80°. This is because during this period, the whole slope subsided, pore water seepage caused small particle translation and rotation, and at last the long axis directions changed a lot. When it came to 60 s (Fig. 13 (d)), the particles presented an irregular distribution, and small diameter particles filled the space between coarse particles. Sand particles in the microscopic observation area in the long axis direction returned to a uniform distribution, and the slope would slide imminently.

Fig. 12 Microscopic particle movement pictures at time (a) 36 s; (b) 48 s; (c) 54 s; and (d) 76 s
B. Area of porosity

The area of porosity is defined as the ratio of pore area to analysis area. The values of area of porosity in 1st observation area at 0 s, 20 s, 40 s, 50 s, 60 s, 66 s and 69 s were used to draw the curve, as shown in Fig. 14. The slope was in infiltration and softening stage from the beginning to 50 s, during which time the area of porosity declined, especially after the time of 20 s. With the increase of moisture content in the slope, serious soil seepage deformation happened; so the area of porosity drop dramatically. However, from 50 s to 69 s, the slope entered the overall slide stage, causing increase in area of porosity. By comparison between macroscopic experimental phenomena and microscopic area of porosity, we can conclude that particle microscopic movement took place earlier than the macroscopic observable deformation of slope body.

The area of porosity at 56 s already started to increase slightly, but it was not until 66 s that an overall slope slide was observed. It is shown that microscopic parameters reflect the macroscopic damage of slope in advance, which should be paid attention to in practical engineering.

Fig. 13 Rose diagrams of the long axis orientation at time (a) 0 s; (b) 40 s; (c) 50 s; and (d) 60 s

Fig. 14 Area of porosity (A) changing over time (t)
3.2.3 Water-soil interaction mechanism

The observation pictures at 32 s and 63 s through the sand slope test are presented in Fig. 15. It is shown that the slope had an obvious boundary of moisture content, above which soil color was relatively deep because of high moisture content. Through microscopic observation analysis, pore water in the high content areas penetrated approximately parallel to the slope bottom, and carried small particles downward at the same time. This led to a significant decrease of the penetration coefficient in the high content areas and formed a transient stagnant layer which made the upper layer in a nearly saturated state (Fig. 11(d)). As shown in Fig. 16 (a), a water bag occurred in the slope on the transient stagnant layer.

The rain as a liquid, may play a role of lubrication, making the friction between the particles decrease little by little. With the rainfall duration, the moisture content of the transient stagnant layer increased gradually. The increase of saturation made contributions to the rise of pore water pressure and the decrease of the soil effective stress. With the friction reducing, the matric suction decreasing and the effective stress dropping, the soil shear strength lost and the soil on the transient stagnant layer liquefied gradually (Fig. 16(b)). When the sliding force of the saturated soil above transient stagnant layer exceeded the anti-sliding force, the slope surface flowed down rapidly. Driven by the internal water flow, a mudslide appeared.

4 Conclusions

1) The essence of simulated coarse sand slope forming debris flow is that local fluidization causes slope sliding as a whole. The movement of small particles forms a transient stagnant layer with increasing saturation, causing soil shear strength loss and local fluidization. When the sliding force of the saturated soil exceeds the anti-sliding force, the coarse sand slope forms debris flow immediately.

2) Centrifuge modeling of a coarse sand slope in the process of forming debris flow mainly consists of three stages, namely the infiltration and softening stage, the overall slide stage and debris flow stage.
3) Pore water pressure has a great effect on the slope deformation and particle movement, which reflects the interaction between the water and soil, and the accumulation of pore water plays an important role in the process of debris flow.

4) Particles move downward mostly and the long axis movement experiences three stages, changing from initial uniform distribution to directional distribution, and then back to the uniform distribution.

References


[10] McArrell BW, Bartelt P, Kowalski J. Field observations of basal forces and fluid pore pressure in a


