EVOLUTION OF DEBRIS FLOW ON HILLSIDE

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***Abstract**:* As one of geological disasters and geomorphological processes, debris flow stemming from loose materials on hillside will menace the safety of highways and railways in mountains. This work is to show the evolution of debris flow on hillside under action of precipitation by modeling in laboratory. One physical model is built in laboratory, in which, length and height of the model are 3.3m and 2.5m respectively, the slope angle is 35.5° , and the thickness of loose materials on the slope is 30±1cm. Precipitation to trigger debris flow is artificial and varies with duration. The modeling identify it is reasonable to divide the evolution of debris flow into four stages with increasing and duration of precipitation, i.e., creep, sliding, flow and deposit. During stage 1 (creep), stability of the slope become weak slowly, creep is dominant and fissures on surface of the slope appear. When loose materials are in saturation, the slope becomes critical status, so stage 2 (sliding) occurs as a landslide. During stage 3 (flow), local torrents on the slope emerge and bigger ravine dominates gradually, then initial debris flow with gas and clay blocks forms, flow velocity and impact force are measured. When debris flow in ravine get to the area of the slope foot, the evolution is in stage 4 (deposit), deposit fan appears. Disasters to highways and/or railways usually produce at the area of the slope foot during stage 3 and stage 4.
***Key words**:* debris flow; hillside; precipitation; evolution; modeling

1 INTRODUCTION

In mountain torrents or melting of ice and snow, intense and localized precipitations may cause flash floods with important sediment transport. Especially, loose materials on slopes easily become debris flow with various rock blocks under action of rainfall (Ning C., 1989). For example, in Northern regions of Mt. Tianshan, Xinjiang province, China, there are about 80 debris flows along 90km of the highway from Dusanzi city to Kuche city, e.g. the debris flow at the 616th km (Fig.1) (Chen H.K., et al., 2004a, 2004b). To reduce the debris flow hazard, it is common to couple structural and non-structural protections (Brufau, et al., 2000). However, to highways or railways in mountain regions, due to abundant loose materials on slope and steep landforms, protections are focus on debris flow in recent years (Kang Z.C., et al., 1989). As an essential aspect, effective protections must be stemmed from reasonable cognition of evolution process of debris flows on hillside. Brufau et al. (2000) developed 1D mathematical modeling of debris flow using the equations governing the dynamics of a liquid-solid mixture. Trygve et al. (2004) provided a better understanding of the mobility of subaqueous debris flow through particle tracking by high-speed video. Richard (1997) approached inertial motion of surge of debris flow using USGS experiment. Gravity flow of cohesionless granular materials in chutes and channels was studied by Savage (1979), while debris flow on prismatic open channel is approached by Takahashi (1980). Chen H.K et al. (2004c, 2006a, 2006b) make some researches on dynamics of debris flow expressed through velocity, impact and abrasion.

Take debris flow at the 616th km along Mt. Tianshan highway as an example, the purpose of this work is to show the evolution of debris flow on hillsides under action of interval precipitation through modeling in laboratory.

Fig.1 Debris flow at the 616th km along Mt. Tianshan highway, Xinjiang, China

2 MODEL DESIGN

2.1 Physical model

Based on the debris flow at the 616th km along Mt. Tianshan highway, Xinjiang, China, assign geometry similarity of the model is 1:100 (Fig.2). Then, level length of the model is 3.3 m, height is 2.5 m, and average angle of the slope is 35.5 degrees, so the length of the slope is 5.6 m, thickness of loose materials on the slope is 30±1cm. The materials on slope are composed of clay, sand and carbonic rocks. Further, real image of the model is constructed as shown in Fig.3.

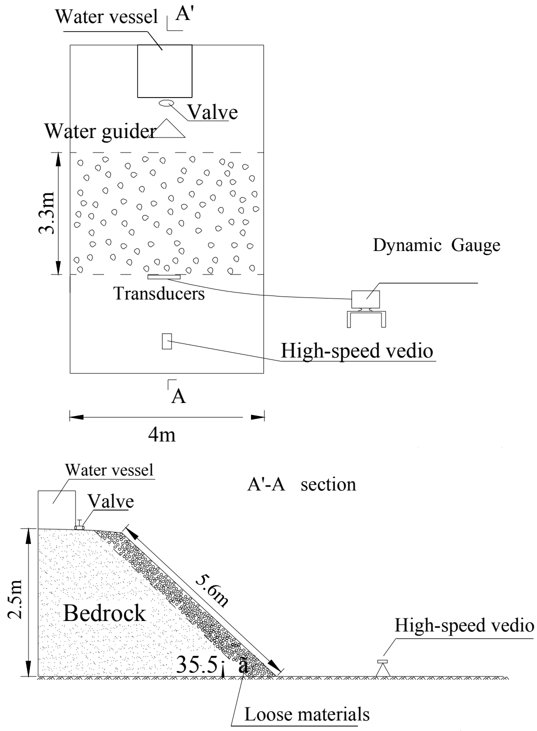

Fig.2 Model design of debris flow at the 616th km along Mt. Tianshan highway, Xinjiang, China

Fig.3 Image of the Physical model to simulate debris flow on hillside

2.2 Precipitation simulation

In evolution of debris flow stemming from loose materials on slope, water by precipitation and/or melting of ice and snow is important and dominant. To present modeling, precipitation is artificial, includes two aspects, one is continuous rainfall in before bursting up, and another focus on rainfall or precipitation in shorter duration. Rainfall in the first stage plays a role to saturate and attenuate loose materials on slope, while the rainfall in the second stage trigger these loose materials to creep and flow. The modeling abides by representative precipitation expressed as Fig.4, which reflects both interval and gradual increase. The maximum precipitation is about 34mm during 10 minutes, simulating heavy or storm rainfall in-situ.

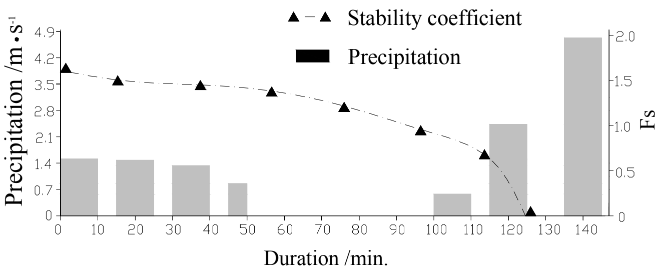

Fig.4 Precipitation variation and duration during modeling

2.3 Similarity analyses

To obtain real velocity and impact force of debris flow at the 616th km along Mt. Tianshan highway, Xinjiang, China, similarity analyses are necessary.

N-S equation in x direction (down slope) is as follows.

$$\frac{D\upsilon_x}{Dt} = F_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 \upsilon_x}{\partial x^2} \tag{1}$$

Governing equation similar to equ.(1) is established.

$$\frac{D\upsilon'_x}{Dt} = F'_x - \frac{1}{\rho'}\frac{\partial p'}{\partial x'} + \nu'\frac{\partial'^2 \upsilon'_x}{\partial x'^2} \tag{2}$$

Due to the one dimensional flow, so

$$C_L = l_p / l_m = 76.8 \tag{3}$$

Where, l_p is length of the slope in-situ, and l_m is length of the slope on model.

Based on similarity principle, the next formula exists through comparison between equ.(1) and equ.(2), then

$$\frac{C_\upsilon^2}{C_g C_L} = 1 \tag{4}$$

Further, due to assume $g = g'$ and $C_L = 76.8$, then

$$C_\upsilon = \sqrt{C_L} = 8.8 \tag{5}$$

So

$$v_p = 8.8 v_m \tag{6}$$

That is to say, flow velocity v_p of debris flow in real time field is 8.8 times of that v_m in the modeling.

Meanwhile, impact force of debris flow on structure or bank of debris flow valley is calculated generally in the following formula.

$$P = k\rho\upsilon^2\cos\theta \tag{6}$$

Similarity equation of impact force in model is as follows.

$$P' = k'\rho'\upsilon'^2\cos\theta' \tag{7}$$

Further, next five formulas exist.

$$C_P = C_\upsilon^2 \tag{8}$$

Due to $C_P = C_\upsilon^2 = 76.8$, then

$$C_P = p / p' = 76.8 \tag{9}$$

That is to say, impact force p of debris flow in real time field is 76.8 times of that p' in the modeling.

2.4 Items of observations

The modeling duration is about 150 minutes, six items are observed and recorded as followings during artificial precipitation.

The first, infiltration and permeability of the loose materials on slope during precipitation.

The second, seepage at both surface and foot of the slope during precipitation.

The third, variation of water content of loose materials on slope of the model with precipitation.

The forth, slope deformation and mass movement on the slope with precipitation.

The fifth, start-up, motion and deposit of the debris flow stemming from loose materials on slope.

The sixth, landform formality of slope after occurrence of the debris flow.

3 OBSERVATION AND ANALYSES OF MODELING IN LABORATORY

With increasing and variation of interval rainfall, debris flow transfer gradually, evolution of the debris flow is classified as four stages, i.e., creep, sliding, flow and deposit. Every stage is described in detail.

Stage 1: Creep

Creep is the first stage for loose materials on the slope to become debris flow under action of precipitation. Many features in the stage belong to soil and unsaturated soil mechanics. Loose materials with natural water content on slope absorb water infiltrating from precipitation and/or melting of ice and snow, and saturate gradually. Further, stability of the slope slowly become weak, creep of loose material is inevitable. As for the model, before testing, density of the loose materials is 20 kN/m^3, cohesion and friction angle between loose material and bedrock are 3.94kPa and 24.51° respectively, stability coefficient of the slope is 1.78 (Tab.1). However, with increasing of precipitations, more and more water infiltrate into the loose materials, tension fissures or cracks on surface of the slope appear (Fig.5).

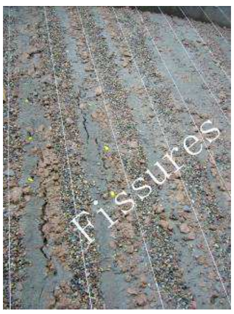

Fig.5 Fissures on surface with increasing of precipitations

Stage 2: Sliding

With saturation of loose materials on the slope, shear strength between materials and bedrock attenuates gradually, and zones with unstable status expand obviously. Further, sliding stage achieve obviously as landslides. To the model, saturated density of the loose materials is 21.9 kN/m^3, cohesion and friction angle between loose material and bedrock become 3.25kPa and 14.27 ° respectively. At the same time, the slope is in critical or limit equilibrium, stability coefficient of the slope is about 1.00 (Tab.1).

It is valuable that the affect of ground water from precipitation can be classified three aspects, the first is softening of materials, the second is seepage force along the slope, and the third is increasing of loose materials weight by water. Calculating using Bishop method indicate that the first aspect makes stability coefficient of the slope to decrease 0.38, the second makes the stability coefficient to decrease 0.32, and the third makes that to decrease 0.08. Therefore, contributions of the three aspects are 49%, 41% and 10% respectively (Tab.2). at the end of the stage, more and more small scale ravines emerge on the slope.

Table 1 Strength parameter between bedrock and loose materials on slope

Status	Cohesion / kPa	friction angle /°	Stability coefficient
Nature	3.94	24.51	1.78
Sliding	3.25	14.27	1.00
Flow	0.19	1.34	-

Table 2 Contributions for aspects to attenuate slope stability

General attenuation	Aspect 1	Aspect 2	Aspect 3
0.78	0.38	0.32	0.08
Percent / %	49	41	10

NOTES:

General attenuation: Attenuation of stability factor

Aspect 1: Material softening after absorbing water and attenuation of strength

Aspect 2: Seepage force in slope

Aspect 3: Weight increasing by saturation of materials

Stage 3: Flow

With occurrence of heavy rainfall, local torrents on the slope emerge markedly (Fig.6). Loose materials near ravines run into these ravines, mingle with water and become solid-liquid two-phase compressible media in ravines. The mixture flow in these small ravines and enlarge these ravines through impact and abrasion. Gradually, large scale ravines on the slope appear, while motion of debris flow in these large ravines appear turbulent and interval (Fig.7). In the stage, the initial debris flow is composed of solid particles and/or clay blocks, liquid water and/or clay slurries and air. Solid particles construct the macro sketch of initial debris flow, and both liquid and air exist in pores of the sketch. As for the model, cohesion and friction angle between loose material and bedrock decrease to 0.19kPa and 1.34°

respectively (Tab.1). At the mouth of ravine near foot of the slope, impact forces are measured by transducers (Fig.8). Variation of velocity both model and in-situ are shown in Fig.9, and three surging are obvious, indicating by A, B and C. Meanwhile, variation of impact strain record as shown in Fig.10, impact force in real time field is 1798.5 kPa calculated by similarity number and testing duration in modeling.

Fig.6 Simulation of heavy rainfall and torrent on slope

Fig.7 Ravine and torrent

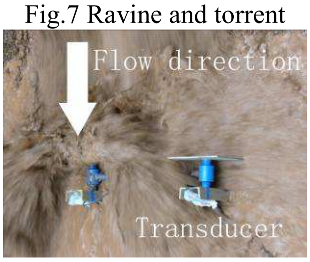

Fig.8 Measure of impact force

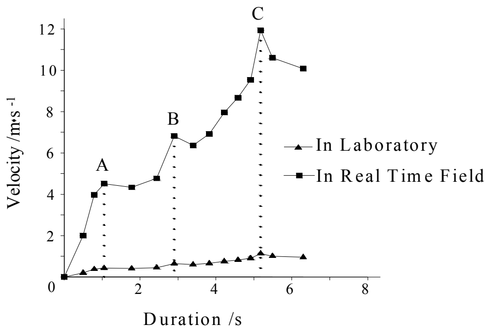

Fig.9 Variation of flow velocity

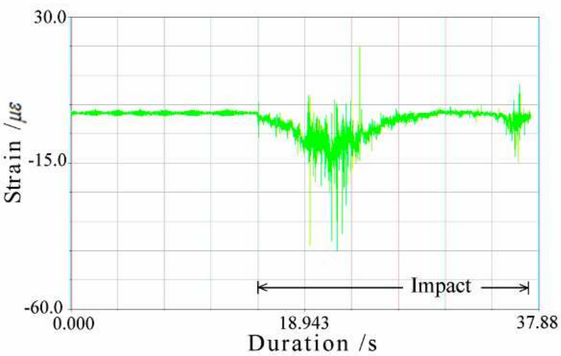

Fig.10 Variation of impact strain

Stage 4: Deposit

When kinetics energy of initial debris flow disappear and transfer the other energy such as heat energy and mechanical energy, debris flow will deposit near the foot of the slope, and deposit fan appears, meanwhile an dominant ravine forms as shown in Fig.11. Formality of deposit fan is consistent to viscosity of debris flow, when viscosity is less than 0.03 Pa.s, the debris flow becomes thin and results in deposit fan extensively and longer (Chen HK, et al., 2004a), while many coarse particles collected at marginal area of the fan. In view of the deposit fan, thin or little viscous feature of the debris flow is deduced. A quite of loose materials piles up as fans near the foot of slopes. Therefore, in mountains, highways or railways to pass from foot of slope with much loose material are impacted and deposited frequently by debris flow.

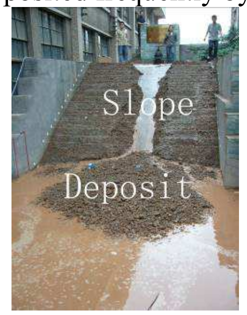

Fig. 11 Landform after occurrence of debris flow

4 CONCLUSIONS

Based on series of modeling in laboratory, it is identified that dynamics of debris flow dominates in control of debris flow along highway. Some conclusions are as following.

The first, debris flow on hillside belongs to a geological disaster developing extensively in western regions of China. Steep slope, abundant loose materials in unstable status under action of rainfall or precipitation, and other triggering agents such as melting of ice and snow or/and earthquake are necessary. Of course, precipitation and/or melting of ice and snow general dominate evolution of debris flow on slope.

The second, to observe the general evolution of debris flow in hillside, a typical physical model in laboratory is constructed by similar to that, a real debris flow at the 616thkm along Mt. Tianshan highway of Xinjiang in China. The duration time of modeling is about 150 minutes with interval and gradual increasing precipitation from zero to 34mm every 10 minutes. The precipitation simulates the gentle precipitation before a storm or heavy precipitation occurring.

The third, four stages for debris flow to develop are concluded through observation in the modeling, i.e., creep, sliding, flow and deposit.

During creep stage, loose materials on slope absorb water from precipitation, saturate gradually, stability decrease slowly, and begin to creep so as to cracks on slope appear obviously.

During sliding stage, shear strengths, cohesion and friction angle between materials and bedrock, attenuate gradually, which causes sliding of loose materials on slope. The affect of ground water in loose materials can be classified three aspects, softening of materials, seepage along the slope, and weight increasing of materials, their contributions to reduce stability coefficient are 49%, 41% and 10% respectively.

During flow stage, local torrents burst out and ravines develop on slope. Further, debris flows with much gas and natural clay blocks and solid clastic forms and flows in ravines. Surging and impact is obvious.

During deposit stage, debris flow fan appear, consolidation of deposit materials occur with loss of water. If bridge is embodied by deposit, additional stress in structures appears with consolidation in the stage, which causes structures damage gradually.

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