

Response to Referee

Dear Referee,

Thanks for your important comments on this manuscript. The authors appreciate the constructive comments. Those comments have been very helpful for the authors to improve this manuscript.

Response to referee 1#

***Overall comment**

The object of this paper is the proposal of a theoretical model for debris flow initiation supported by one laboratory experiment. The writer identified the following main deficiencies:

1. Author mix different types of debris flow triggering both in the introduction and model development.
2. Authors use material with 90 % of gravel (> 2 mm), which is a cohesionless material: how can they measure cohesion in dry conditions?
3. Presentation of the laboratory experiment is very poor.
4. Findings of both theory and laboratory are not consistent.

Response:

Thanks for referee's comment. In this paper, the original idea is to propose a theoretical model for shallow failure under hydrodynamic condition. For the debris flow initiation, it still needs a complex transformation process which is not the key studying point in our paper. So the related content which may cause misunderstanding has been modified in the revised version (see details in supplement).

Detailed comment 1

(1) The debris flows are divided in two categories: landslide failure debris flows and runoff generated debris flows. Landslide failure debris flows are usually ruled by viscous or Coulombian rheology and runoff generated debris flows are usually ruled by grain-inertial rheology. As a consequence landslide failure debris flows are composed by slurries or gravel within a slurry matrix. Runoff generated debris flows are mainly composed by gravel. Experimental results of Gregoretti (2000a,b) and Tognacca (2000) shows that in case of granular material debris flow is triggered by runoff that entrain the solid material. As size material of the authors is 90% larger than 2 mm, that is 90% is gravel, the material is assumed granular and debris flow triggering is due to runoff. Then authors should concentrate only on runoff generated debris flows.

Authors that studied runoff generated debris flows in the field are:

Berti and Simoni, 2005; Cannon et al., 2008; Coe et al. 2008; Gregoretti and Dalla Fontana, 2008; McCoy et al., 2012; Theule et al., 2012; Kean et al., 2013.

According to Kean et al. (2013), models of Armanini and Gregoretti (2005), Lamb et al. (2008), Gregoretti et al. (2008) and Recking (2009), provide a framework for determining exactly the critical discharge for the starting of sediment entrainment in a water flow. Friendlier approach is the empirical one of Tognacca et al. (2000) and Gregoretti and Dalla Fontana (2008) based on flume data. The writer does not understand the introduction of the hydrologic model of Berti and Simoni (2005) because it models the kinematic routing of a water flow in a channel and not the formation of runoff due to rainfall in the upstream contributing basin.

Response:

Thanks very much for the referee's suggestion. The original intention of this paper is to analyze the shallow failure process with unconsolidated soil under thin water flow and construct corresponding model. After accepting the referee's suggestion and reanalyzing our tests results, authors all agree that the shallow failure on slope is not always triggering the original debris flow. And only a small part of them can trigger debris flow under certain water flow condition. Here, because the debris-flow initiation mechanism is not the key point, the title which has been modified as "A theoretical model for shallow failure on unconsolidated soil slope considering overland and interstitial flow" should be more suitable to the idea in this manuscript. Meanwhile, the Introduction and partial conclusion also have been revised to come to an accord with the title. We believe this modification will clearly show its highlights as follows.

- (1) The shallow failure mechanism and process with widely graded and unconsolidated soil is shown in detail.
- (2) Fine particle migration under rainfall and runoff has been analyzed and its effect has been considered to construct a numerical model for shallow failure.

For the types of debris flow initiation, authors agree with the Referee's points that debris flows are divided in two categories: landslide failure debris flows and runoff generated debris flows. And only rainfall can't trigger debris flow. With plenty of water like the thin runoff condition, the shallow failure would rapidly transform to primitive debris flow. And this type of debris flow is also not similar to the debris flow triggering by water flow in channel.

Here, we only want to show and analyze the shallow failure process with widely graded and unconsolidated soil. The debris flow forming from landslide or shallow soil failure which belongs to hydraulics is not the main content in this manuscript.

So, considering the hydrodynamic effects which contain the fine particle migration forming local perched water table, superficial shear stress and interior seepage force, the criteria and mechanism of soil failure with widely graded and unconsolidated soil have been studied and analyzed. (**See in Discussion, Line 360~372**)

Detailed comment 2

(2) Material used in the experiment being is granular because 90% of it has size larger than 2 mm, that is, it is mainly composed by gravel. So it is very curious that cohesion due to only to the clay (not to sand or lime) appears. In some cases it is due to a dilatancy effect when there is a decrease of shear after a peak value but this is not visible in figure 5. Authors should justify their findings. It is also curious that cohesion disappears in saturated conditions and that internal frictional angle changes about 15%. Data of Tubino and Lanzoni (1993) show that difference in friction angle between dry and saturated condition is less than 5%.

Response:

Thanks referee for pointing out this problem. In fact, the materials in our experiment contain some clay (Based on the laser-phase Doppler analyzer, the clay percent content is about 5%), therefore the soil is showing a little cohesion. In the experiment, the superficial fine particle (particle size is less than 2mm) is migrating from surface to slope inside. So the grading of superficial soil has changed. Especially with the decreasing in fine particles, the superficial soil will show a nearly-zero cohesion and lightly reduced internal friction angle (**see details and modification in Lines 140~151**).

Detailed comment 3

(3) Experiments: measures of the flume size (length, width...) are missing. A detailed description of the experiment is missing: where the inflow of runoff? The figure 1 does not explain it and a sketch of the experimental facility is missing. Experiments with rainfall have very few senses. Assuming, from figure 1, 3 m flume length and 0.3 m width the supplied discharge is $140 \times 0.001 \times (3 \times 0.3) / 3600 = 0.00035 \text{ m}^3/\text{s}$ that is very low. The triggering of debris flow in a location is due to the stream flow given by the excess rainfall in the upstream basin. The rainfall fallen in channel reach of some meter is not able to form runoff. The fact that inflow is not specified, forbids the writer from understanding the entrainment mechanism of granular material. The writer, as the large runoff seen in Figures 4, suspect both an overtopping (figure 4a) and head cutting due to emerging seepage (figure 4b). In both the cases granular material is entrained by runoff and not by a landslide failure mechanism. About that see the experiments of Liao and Chou (2003), Huang et al. (2007) and Gregoretti et al. (2010). Moreover, the meaning of the three layers that compose the slope and their influence on debris flow triggering is not introduced.

Response:

Thanks very much for the referee's comment. In this manuscript, the runoff is provided by a water tank which can control flux and simulate the superficial flow on the slope. Though it can't reach a steady state, whole flow velocity of this overland flow can be regard as the same value because of its shallow depth. And, the detailed design is shown in Figure 1 (See in Figure 1, Line 82).

Moreover, the main idea of this manuscript is to analyze the failure process and mechanism of widely graded and unconsolidated soil under rainfall and runoff. And it is similar to the landslide failure process (Iverson, 1997) and the post-fire slope instability (Well, 1992). And the soil failure is occurring on the unconsolidated slope, not in the channel. So it decides the soil failure and thin debris flow formation are similar to the phenomenon of Wells (1987) and Gabet (2003). Though the debris flow is not always triggered after shallow failure in our experiment which needs a transforming process, it can show a supply mode of source material for debris flow. And this transformation condition is not in the scope of this manuscript.

About the failure mechanism, the soil used is widely graded material which contains little clay but still has some cohesion. So, if it was regard as granular material which has no cohesion, the fine particle migration and local water perched table can't be formed and shallow failure would not happen due to large permeability of granular material. In fact, the fine particle would migrate, block pores and form local relatively impermeable layer. Then the shallow soil above this impermeable layer would move under hydrodynamic and self weight effect (shown in Figure 3). Though this process couples with the single particle movement, the main mechanism is shallow slide with local soil. Authors think that some current research is mainly focusing on pure granular material such as homogenous sand soil or gravel (Huang et al, 2007; Gregoretti et al. 2010), which may not reflect this phenomenon and mechanism in this manuscript. (See details in Line 146~163)

Additionally, due to our flume requiring large amount of soil material for each trial, we placed the soil material layer by layer at three times. So the three layer soil may have small difference in grading.

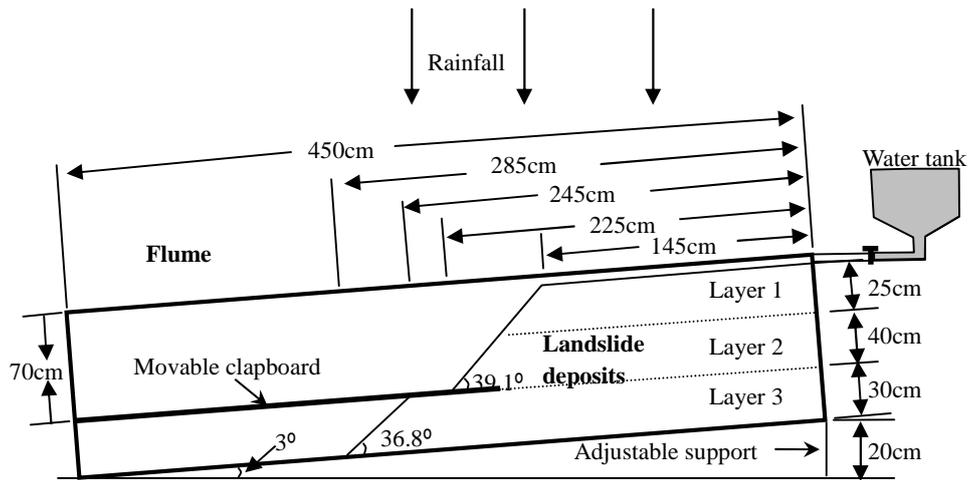


Figure 1. The design of flume

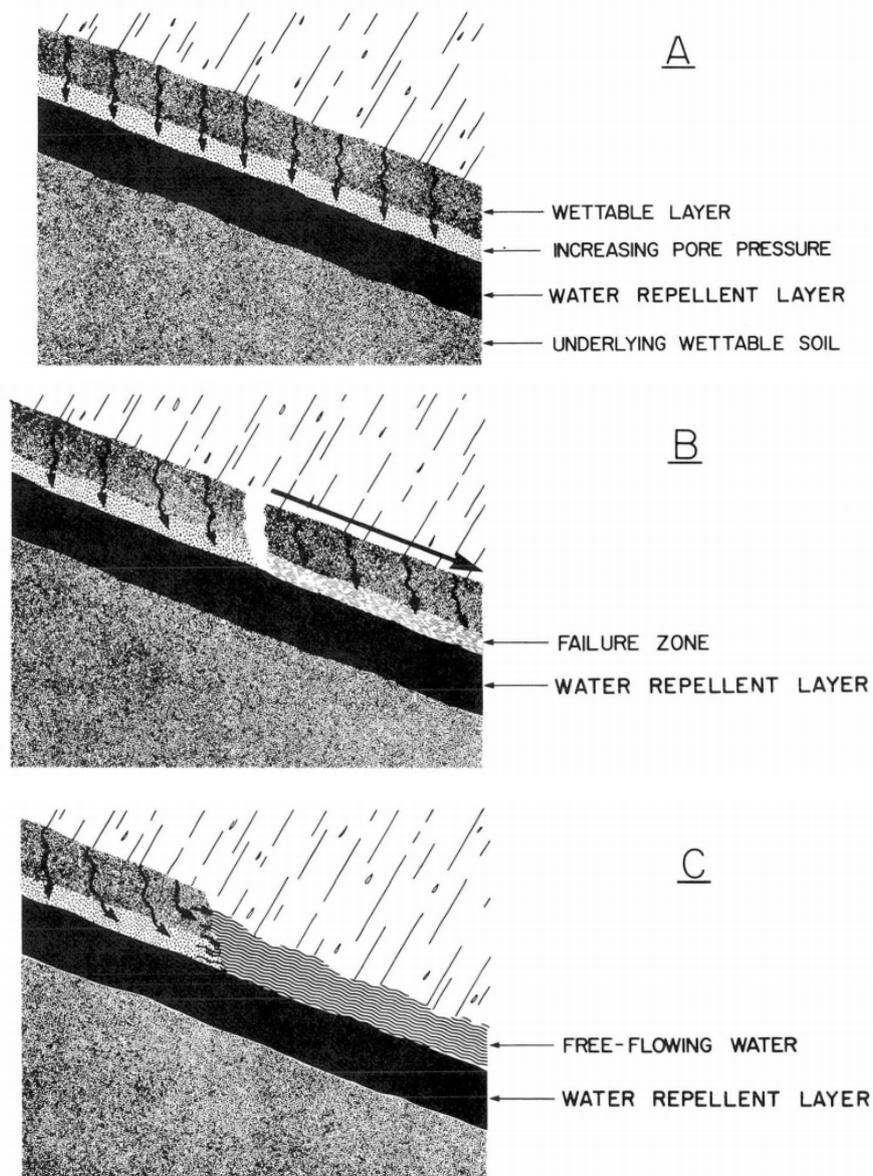


Figure 2. (A–C) Sequential events leading to the initiation of thin debris flows. During a rainstorm, the hydrophobic layer creates a perched water table that may cause a small debris flow, from Wells (1987)

Detailed comment 4

(4) The model does not seem consistent with the experiment because entrainment of material seems due to surface erosion of particles caused by overtopping flow or the emerging of seepage flow and not to the slide of a layer of particle. Moreover, model sketch of figure 7 (bottom parallel to the slope) is not consistent with the experiment (bottom horizontal). Another issue is that flow depth and velocity are not parameters of model but real physical quantities otherwise is not possible apply the model for different slope angles. They should be the quantities measured during the experiment. Finally model should be tested with several experiments carried on varying the slope angle in a range of possible values.

Response:

Thanks very much for the referee's comments. The bed of flume is not flat but with a gradient about 3° . The detailed description is shown in Figure 1. **(See details in Line 77~83)**

For the conclusion of experiment, we believe that the shallow failure is caused by hydrodynamic and self effect. The detailed analysis and reasons are as follows:

- (1) The experiments in this text are a physical model simulating failure process on slope not in channel. So the hydraulic conditions (the water flow in channel is much larger than it on slope) are different which result in the different failure mechanism.
- (2) Soil materials here are widely graded and unconsolidated soil which has certain cohesion before experiment and lost cohesion after experiment. At the meanwhile, due to the hydrodynamic effect, the fine particles (<2 mm) would migrate down the slope, accumulate in some local positions forming a local water perched table, and then lead to shallow failure. This process is similar to the post-fire slope failure (Wells, 1987).

Shallow failure is the main phenomenon, which contains local soil slide on the water perched table, and also single particle movement. However, the thin water flow on slope can't trigger single particle moving, unless firstly fine particle migrating and then large particle moving under self-weight. Moreover, due to the fine particle migrating in the shallow slope, the failure is always occurring in the shallow position on the slope **(Details is shown in Figure 3)**.

Though the granular material in channel is always triggering and transforming into debris flow by large runoff with the particle movement mechanism (Tognacca et al, 2000; Gregoretti and Dalla Fontana, 2008), the shallow failures or landslides are not always transforming into debris flow because they are always determined by topography and water flow condition. Owing to its complexity, this debris flow initiation process and mechanism are only discussed briefly in this text.

About all, the soil material, topography and hydrodynamic conditions which have great differences determine the different experiment result. Then the debris flow initiation mechanisms are also different though it is not our main studying content in this paper.

We also regard that flow depth and velocity are not parameters of model but real physical quantities. The model in this manuscript is formed by theoretical derivation, and it can be applied for different slope angles. **(See details in Section 3.3, and Table 3)**

About the model verification, though we repeat our experiment many times with two bed gradient, it is difficult to change the bed gradient with this huge flume to verify this model. In the future, we will get more field data and small-scale experiment data to improve this model.

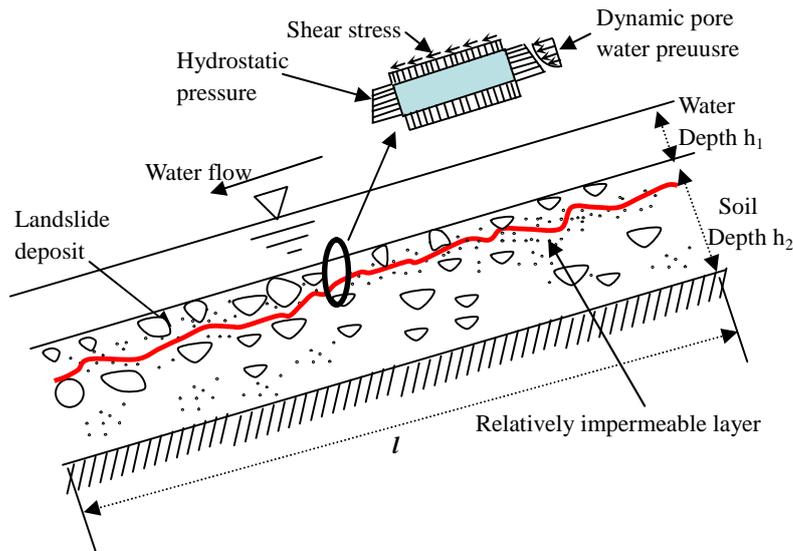


Figure 3. Simplified assumptions for the stress distribution of unconsolidated soil under hydrodynamic conditions

Response to referee 2#

***Overall comment**

Influence of rainfall on the stability of an unconsolidated landslide deposit slope was investigated experimentally by the authors. Findings from the experiments are of great value to interpret mechanism of the debris flow. The manuscript deserves to be published. However, 3 suggestions for its revision are given in the following.

Response:

Thanks for referee's comment. Under rainfall condition, shallow failure soil on the unconsolidated slope with widely graded and loose deposits is the main source for slope debris flow. Meanwhile, shallow failure is an important process before debris-flow initiation. Therefore, shallow failure mechanism and prediction model in this paper provide certain basis for analyzing debris-flow initiation.

Detailed comment 1

It is a little bit difficult to understand debris gradations tabulated in table 2, debris sized 60~80 could not be traced after experiment. It is therefore suggested that the authors explain this in the manuscript. Moreover, depths of the three layers of the debris deposits need to be specified in order that readers may understand the experiment results easily.

Response:

Thank you for the referee's suggestion. In table 2, we wanted to illustrate the sample soil which has the particles with size of 60~80mm. And in the experiment, the particles larger than 60mm are removed for avoiding the scale effect. **(See details in Table 1)**

Additionally, due to our flume requiring a large amount of soil material for each trial, we placed the soil material layer by layer at three times. So the three layer soil may have small difference in grading.

Detailed comment 2

Shear strength of unsaturated debris deposits (in table 3) seems irrelevant. It is suggested that a detailed description for its usage is given. Further, sampling location for the direct shear tests as well as the gradation of the debris should be stated since the strength is closely related to the interlock of the debris, particularly after the process of “coarsening” due to rainfall.

Response:

Thanks very much for the referee’s comment. In fact, the materials in our experiment contain some clay (Based on the laser-phase Doppler analyzer, the clay percent content is about 5%), therefore the soil exhibits a little cohesion. In the experiment, the superficial fine particle is migrating from surface to slope inside. So the grading of superficial soil has changed. Especially with the clay decreasing, the superficial soil will show a nearly-zero cohesion and lightly reduced internal friction angle. The shear strength of unsaturated debris deposits is used to analyze the slope stabilization in different state.

And sample of soil in this manuscript is from Wenjiagou Gully in Qingping area, southwestern China. (See details in Line 172~178, 77~78)

Detailed comment 3

It is strongly suggested that writing is re-examined by the authors (and preferably by an English native speaker). Several errors are found in the manuscript, e.g. the line 323 (details are in section 4.2), the line 351 (F should be f), etc.

Response:

Thank you for the referee pointing out some errors. And we have checked the manuscript again and the detailed revise is as follows:

(1) In **line 217**, the soil surface friction provided by the surface flow f is interpreted as below.

The hydrodynamic effect on the soil surface can be simplified into shear stress along the slope surface and dynamic pore water pressure except the hydrostatic pressure. The shear stress analysis of f is shown in **Figure 7 and Line 229~250**.

According to hydraulics theory, the shear force F that is generated by the surface flow on the slope surface can be calculated as follows:

$$f = \lambda \rho v^2 / 8$$

where ρ is the density of water; l is the slope length; λ is the friction loss factor of the hydraulically open channel, and when the thin water flow is laminar flow ($Re < 2000$, Re is Reynolds number), $\lambda = 64/Re$; when it is turbulent flow ($Re > 2000$), $\lambda = 1/[21g(3.7R/\Delta)^2]$ (Nikuradse empirical formula). $R = A/\chi$ is the hydraulic radius of the cross-section; and Δ is the roughness (slope surface sand diameter), which is usually close to 30-60 mm in a pebble river bed.

(2) In **line 351**, the shear force ‘ F ’ should be ‘ f ’. It has been corrected in the manuscript.

(3) The hydrodynamic effect in the soil inside is omitted. And it may be an important force for the soil failure and shallow slide. The detailed analysis has been added in the section 3 (Line 251~263).

Water pressure in the soil is generally divided into hydrostatic and dynamic pressure. Owing to the dynamic pore water pressure always generated by soil contraction or seepage, the superficial widely graded soil doesn't have this effect at saturated state with fine particle lost. However, the Reynolds stress from turbulent mixing in pore water which can be regarded as dynamic water pressure should not be ignored, although it has a small value (The detailed description is shown in Figure 7). Hotta, et al (2011) constructed a theory formula about Reynolds stress in debris flow. But in soil, this stress has few literatures to analyze. So we proposed an empirical formula to forecast this stress. The formula is as follows:

$$p_d = A\rho v^2$$

Where p_d is the average Reynolds stress on the cross section of shallow failure layer, kPa; A is empirical constant, called dynamic pore water pressure coefficient. Generally for the pure water, it is 0.5; ρ is the pore fluid density, kg/m³; v is pore fluid velocity, m/s. Here, the Reynolds stress is in fact the impact stress by pore fluid.

(4) The writing of this manuscript has been carefully examined and corrected.

Response to referee 3#

*Overall comment

This paper presented a theoretical model to analyze the initiation of debris flow. This is an old but interesting topic. First the authors summarized the advances in this area. Then they presented a theoretical model based on experimental observation. This paper has some problems should be clarified.

Response:

Thanks for referee's comment. Based on physical model experiment, present model in this paper is proposed by considering hydrodynamic effect which is usually omitted in current realization. Hence, it is more accurate to forecast soil failure on the slope with widely graded and unconsolidated soil.

Detailed comment 1

(1) Since in experiments the particles with diameter larger than 60mm excluded, the data of "cumulative ratio" should be modified in Table 2.

Response:

Thanks very much for the referee's suggestion. The cumulative ratio of "80mm" has been deleted because the particles with diameter larger than 60mm have been excluded. And Table 2 has been corrected as follows.

Table 2 Particle size distribution characteristics of the soil used in the experimental test

Grain size(mm)	Cumulative ratio (%)		
	First layer	Second layer	Third layer
<60	100	100	100
<40	100	90	82
<20	40	60	72
<5	10	28	40
<2	10	18	10

Detailed comment 2

(2) The description of the experiment should be detailed introduced. How much is the size of flume? How to layout the artificial rainfall apparatus? Were the artificial rainfall and water flow occurred at the same time or rainfall happened first and then water flow happened? The author said that water flow was supplied by an other flume in experiment. But in practice it is most formed by rainfall. So the water is changed with rainfall intensity and duration. To adopt a water flow with stable depth and velocity in analysis is very idealized. At least this point should be an assumption. Actually the change of flow depth has obvious effects on the initiation of debris flow because it can cause excess pore pressure and increasing pore pressure gradient.

Response:

Thanks for your comment. The detailed flume size and layout of artificial rainfall apparatus and runoff supply have been shown in **Figure 1 and Figure 4**.

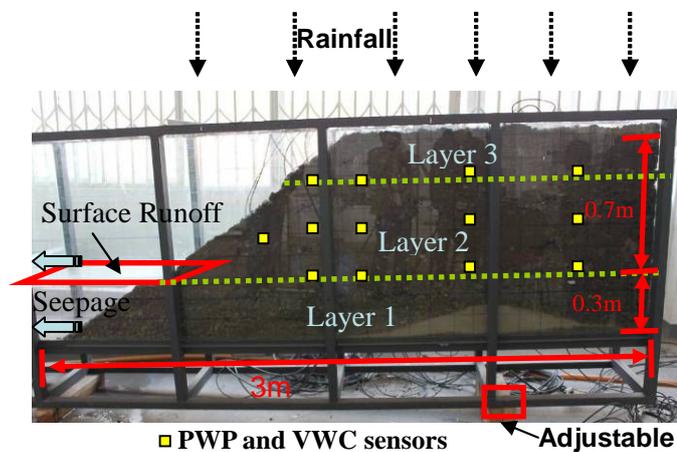


Figure 4. sketch design and actual shape of the flume: artificial rainfall test equipment for unconsolidated soil (PWP and VWC are the pore water pressure and volumetric water content, respectively)

And in section 2.2 and 2.3, experiments with runoff are considering the rainfall alone, and experiments with runoff are considering the runoff meanwhile with rainfall.

The detailed condition and layout should be introduced to avoid a confusion, and it has been added in the manuscript (see details in line 72~75, 115~117, and Figure 1 in manuscript).

In this manuscript, the overland flow is provided by a water tank which can control flux and simulate the superficial flow on the slope. Though it can't reach a steady state, whole velocity of this overland flow can be assumed as the same value because of its shallow depth. Additionally, due to the small catchment area in flume experiment which can't simulate the actual thin sheet flow, a water tank is applied to supply the runoff condition. The water depth is sensitive to soil failure and debris flow initiation, so that the runoff is strictly controlled with shallow depth.

Detailed comment 3

(3) Eqs.(12) or (14) can only be used in case of infinite condition or $a \ll l$. In the experiment (Figs.2,4), the failure is more like a finite model. Other methods such as circular slide method may be more suitable in this case.

Response:

Thanks for the referee's suggestion. Eqs(12) and (14) in old edition are only used in case of infinite condition or $a \ll l$. However, in this manuscript, it is suitable for shallow failure because:

(a) Though the experiment slope is much smaller than field condition, shallow failure size is smaller comparing with the whole slope.

(b) Fine particle migration and blockage effect would form local water perched table which is distributed in layered mode. And this water perched table can be seen as the slide surface for shallow failure.

Except the above, circular slide is more suitable for large-scale or deep landslide. And in these conditions, the circular sliding surface is difficult to get accurately, which is always instead by searching critical slip surface. In the shallow failure model, the sliding face is always formed by fine particles migration and accumulation which can be predicted through analyzing the fine particle movement or empirical formula.

Detailed comment 4

(4) Depth of initiation "a" cannot be a factor to analyze the sensitivity. It is a dependent variable determined by independent factors such as rainfall intensity, water flow velocity and parameters of soil layer. Because the material has only 10% of particles with diameter less than 2mm, the cohesion can be ignored. So it can be excluded from Eq. (14) and the sensitivity analysis.

Response:

Thanks for the referee's comment. The parameter "a" should not a factor for analyzing its sensitivity. And it has been modified in section 3.2 and deleted from sensitivity analysis in section 3.3. And due to the widely graded and unconsolidated soil has little cohesion, the item of cohesion can be ignored and sensitivity analysis (see details in section 3.3 and Line 264-273, Table 3).

The following simplified form of two-phase flow equations will be used (Cheng et al, 2001; Lu and Cui, 2010a, b;). These equations are based on the assumption that the flow is one dimensional and the wall friction and inertia effect may be neglected. Only the simplest form of interaction between sand grains and water, namely Darcy's law, is taken into consideration.

$$\varepsilon(x, t) = \varepsilon_0(x, 0) + \frac{\lambda}{Tu^* \varepsilon_0(x, 0)} \int_0^t U(\tau) d\tau + O(\lambda^2)$$

where $\varepsilon(x, t)$ stand for the porosity at the depth of x and time of t ; $\varepsilon_0(x, 0)$ is the initial porosity for soil material; $U(t)$ (unit is cubic meter every second- m^3/s) is total flow charge at unit cross-sectional area; t (unit is second-s) is the time; L (unit is meter-m) is the soil thickness; λ is a small parameter, employed to obtain an asymptotic solution; T and u^* are empirical constants.

Detailed comment 5

(5) It'd better provide more experimental results to support the theoretical results. This paper should be carefully revised before publication.

Response:

Through the current literatures (Tsai, 2008; Gabet & Mudd, 2006; Kean et al, 2013; Gabet, 2003;), we can find that though the flow depth, pore water pressure, even the porosity, the soil strength and failure depth are still difficult to measure for simulation and verification. In this manuscript, similar to

Iverson(1997), measured data in the experiment can satisfy the need of computation and verification. Moreover, keeping the variable and parameter values constant except the cohesion, Iverson model (1997), Takahashi model (1991) and presented model are compared in **Section 4**. The results show that presented model is safer than the other two models with smaller safety factor. Thus, two advantages which are the sliding face forecast and rational assumption considering hydrodynamic effects will be more convenient and simpler to predict shallow failure even the debris flow event.

About the model verification, though we repeat our experiment many times with two bed gradient, it is difficult to change the bed gradient with this huge flume for verifying this model. To verify the correction of our model, we will get more field data and small-scale experiment data to improve this model.

Reference

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