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The research on the movable solid materials under seepage flow effect in debris flow source area

Shun Yang [a,*], Guo-qiang Ou [b], Hua-li Pan [b], Zhong-sheng Xie [a], Dong-xu Yang [a]

[a] *Technical Center for Geological Hazard Prevention and Control, CGS, Institute of Exploration Technology, CAGS, Chengdu 611734, China*
[b] *Institution of Mountain Hazard and Environment, CAS, Key Laboratory of Mountain Hazards and Surface Processes, CAS, Chengdu 610041, China*

Abstract

Solid materials distributed on the surface of watershed transform to debris flow under seepage flow effect is one of the most common disaster type in the mountainous area, especially in the Longmen Fault regions, China. The high frequency of debris-flow event takes a big menace to local people's safety of life and properties directly, as well as the reconstruction work. Currently, more theory and experiment researches are concentrated on solid materials instability mechanism, debris-flow initiation, movement process of slope-gully system, but fewer research are focused on the moveable critical condition of solid materials under hydrodynamic condition as seepage flow and surface flow. Thus, based on the mechanical balance, through define the theory of the movable solid materials firstly. Then, take a comparison with traditional terms as loosen solid materials, dynamic reserves and efficient solid materials, it found that solid materials move or not is a mechanical problem rather than traditional definition. Thirdly, on the condition of saturated seepage flow, according to setting up geological model and taking mechanical analysis, it gained dynamical formula and resistance formula respectively, then, give confined parameters, it found a liner distribution of dynamical value and resistance value versus depth when the geology model is homogeneous and the seepage flow saturated in whole layer.

Key words: Debris-flow Area; Seepage Flow Effect; Solid Materials

1.Introduction

Debris flow is a flow of a sediment–water mixture driven by gravity, which related to factors as geological tectonics, topographical conditions, hydrology and human engineering et al (Zhou et al., 1991; Xu, 2010). It has been reported that in over 70 countries in the world and often causes 5 severe economic losses and human casualties annually, which seriously retarding social and economic development (Degetto et al., 2015; McCoy et al., 2012; Hu et al., 2016; Cui et al., 2011; Dahal et al., 2009; Liu et al., 2010). According to Takahashi, The mechanical triggers of debris flows can be classified into three types, namely erosion by surface runoff, transformation from landslides, and collapse of debris dams (Takahashi, 2007). Through different water content before debris-flow initiation, Brand et al concluded that the thinner layer failure by rainfall infiltration which result in the weight increasing and the minor of the matrix suction (Brand, 1981). With the different water content between debris-flow initiation and failure, Johnson definite movable index MI (Johnson, 1984), based on the MI, Ellen put forward the index as AMI and set standard as AMI > 1, the debris is easily flow along the gully, while the AMI<0.45, it could not form debris flow (Ellen et al., 1987). Similarly, Takahisa through carried out experiments, it got that when the ratio of l/h<4.0, the landslide materials could not move as debris flow, while the ratio of l/h>7.5, it easily to form debris flow (Takahisa, 1981). Generally, the gravity and hydrodynamic are the mainly driven forces to form debris flow (Howard, 1988; Hongey et al., 2006). With numerous experiments and field survey, it also found that the pore water pressures increased while the loose solid materials moved with surface water, which lead to liquefaction (Wang et al., 2003; Iverson et al., 2004). Based on laboratory experiments and field observations, Wang based on fluid mechanics

* Corresponding author e-mail address*: yangshun09@foxmail.com*

theory, obtained a flow movement equation for the deposit surface and shear stress, but those equations ignored the influence of the pore water pressure on the shearing strength and parameters that could change with time (Wang et al., 1990).

As is known to all, loosen solid materials is one of the essential condition of debris-flow formation, for the numerous solid materials in the watershed, how many solid materials would form the debris flow and how the debris flow moving is also the question. As to the volume calculation, currently most calculations mainly lie in statistics. Actually, plenty of debris-flow researchers carried out numerous studies on debris volume research, such as the volume and distribution of loosen solid materials, traditional concept of effective solid materials (Qiao et al., 2012; Tang et al., 2011; Zhou et al., 1991), those researches take a positive effect for debris-flow prevention and reconstruction post-earthquake. However, most of those methods are mainly based on the field survey and statistics, lack of physical and mechanical meaning. Thus, based on the analysis of debris-flow formation, it can conclude that loosen solid materials whether move or not under hydrodynamic condition in source district is decided by dynamic force and resistance which is a physical and mechanical problem, rather than broadly qualitative description, that is the movable solid materials problem (Yang et al., 2014).

In this context, the study is on condition of mechanical equilibrium principle, definite the movable solid materials of debris-flow source area first, which articulate the movable characteristics of solid materials under hydrological condition in debris-flow source area. Secondly, take a contrast with available traditional definition as dynamic reserve, effective solid materials and movable solid material. Last, take saturated seepage flow as an example, through build geological model and mechanical analysis, to test and verify the formulas by experiment. The research provides a quantitative calculation method of the loose solid materials in the shallow landslide areas, which can favor for the design of the small watershed debris-flow prevention.

2. Definition of the movable solid materials

2.1Definition

Currently, most solid materials calculation in the small watershed are statistics and estimation, the direct question of those method could cause the error of statistics is between 70 to 150 percent. As to the debris-flow check dam design, the unreasonable loose solid materials volume can result in high cost or low prevent ability. Therefore, based on the Yang's research (Yang et al., 2014), it proposed the concept of critical movable solid materials, which can be definite that when the composition force of hydrologic and the gravity components is larger than the resistant, the critical thickness is the cross point beneath the surface slope, as seen in Fig 1.

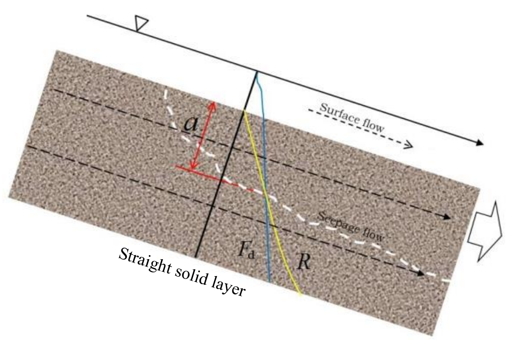

Fig. 1. General map of the movable solid materials

When Fd $<$ R, the whole layer of loosen solid materials is in stable state. When Fd $=$ R, the layer of loosen solid materials is in critical state. While Fd $>$ R, the loosen solid materials within the critical depth would lose failure, seen formula (1) as follows. In summary, the movable solid materials is the solid materials within the critical depth when Fd $=$ R.

$$\text{Critical fomula of movable solid materials} = \begin{cases} Fd < \mathrm{R} & \text{stable state} \\ Fd = \mathrm{R} & \text{critical state} \\ Fd > \mathrm{R} & \text{fail to move} \end{cases} \quad (1)$$

2.2 Contrast among movable solid materials and traditional conception

As to debris-flow prevention design, the volume of loose solid materials is one of the most important parameters. Many researcher focused on the solid materials condition of debris flow, numerous researches are mainly using loosen solid material, dynamical reserve and effective solid materials et al., but the research method lies in quantitative description, field survey and experiences calculation. The contrast between movable solid materials and traditional concept is seen in Table 1.

Table 1. The contrast between movable solid materials and traditional conception

	The Movable Solid Materials	Loosen Solid Material	Dynamical Reserve	The Effective Solid Materials
Concept	When the sum of the hydrological force and gravity component equal to the resistance, the solid within the critical depth	Loosen solid materials distributed in the widely surface	The potential solid materials to form debris flow in source area	loosen solid materials of slope and gully bank fail to move by water saturation and scour, especially to join the next debris flow's solid materials
Volume calculation method	Calculation by mechanical model	Estimate the area and depth in debris-flow watershed	Investigate the area and depth of the potential debris-flow watershed	Estimate the area and depth
Mechanical meaning	Mechanical equilibrium	none	none	none

Solid material is a defined qualitative concept in traditional statement, but what kind of loosen content will form debris flow under hydrologic condition still not appeared in literatures so far. In practical application, mostly loosen solid materials volume calculation is by field survey estimation. As to debris-flow dynamical reserve, which is loosen solid materials volume calculated by measuring length, width and estimated potential thickness, the problem is the estimated thickness originated from investigating outside and there is none practical meaning, actually, the thickness should be controlled by mechanical properties of solid materials. The effective solid materials is just defined as solid materials which joined in the debris flow under water effect, this concept did not applied in actual example currently.

Whether the loosen solid materials on the slope is move or not and how many solid materials could be arised by the rainfall is a mechanical problem, which should be decided by its propulsion and resistance. The dynamic propulsion is mainly including seepage flow and surface flow's component, gravity component, as to rainfall debris-flow pattern, the dynamic propulsion could be calculated by rainfall, runoff and convergence under a certain rainfall frequency. The resistance is constituted of cohesion, friction and shear resistance among particles. The concept of movable solid materials is just based on the mechanical balance, which possess clear physical meaning and distinguished from traditional definition essentially.

3 The Movable Research under Saturated Seepage Flow

3.1 Geology model

It is known to all that the deposition mode and the amount of loosen solid materials in the debris-flow watershed affect the thickness of solid materials. The mechanical characteristics, the longitudinal slope and the difference of hydrodynamic effect also determined the thickness. As to the movable solid materials which is controlled by the relationship among the slope angle, hydrodynamic, gravity and resistance. When the resultant of hydrodynamic component and gravity component is larger than the resistance, the solid materials fail to move and even form debris flow finally.

Water is the essential parts of debris flow, which are mainly come from rainfall and ground water. The movement forms lie in saturated seepage flow/ non-saturated flow and surface flow. As to saturated seepage flow condition, take the loose solid materials firstly, the geology model as Fig. 2 shown.

Geology model conditions described as follows.

- The particles are the heterogeneous anisotropy; the porosity of the detrital grain layer is n.
- The thickness is D, slope angle is θ.
- Surface water thickness is H, when none of surface water, H=0.
- The bottom plate is impermeable and the whole layer distributes saturated seepage.

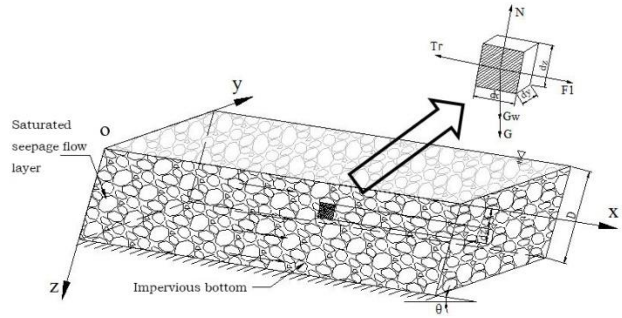

Fig. 2 The general view of geo-model under saturated seepage flow condition

3.2 Mechanical analysis

When the slope angle is less than the repose angle of deposition, the loosen solid materials stay in a stable state. But with a certain hydrodynamic of seepage and surface flow's effect, the balance would be disturbed and the deposited loosen solid materials would fail to move in debris flow. The seepage force and the drag force by surface flow are the mainly hydrodynamic form, the formulas see as following.

The seepage force is related to hydraulic gradient, the formula is seen (2).

$$F_1 = \gamma_w jV \tag{2}$$

where γ_w is water density, j is hydraulic gradient, $j = \Delta h/\Delta L$, Δh is water head difference or head loss, ΔL is seepage path, $\Delta h = \Delta z + \Delta p/\gamma_w + (\Delta u)^2/2g$, Δz is the position head difference, $\Delta p/\gamma_w$ is pressure head difference, $(\Delta u)^2/2g$ is flow velocity head difference.

With saturated seepage flow, select a micro-element body $dxdydz$ along slope incline direction of any depth to take mechanical analysis. It found that the micro-element are mainly suffered gravity, seepage force and shear resistance of particles et. al, as Fig 2 shown.

3.3 Gravity of soil and water dG

At any depth z, the saturated slope layer dG can be expressed by formula (3).

$$dG = \gamma_{sat} \frac{z}{cos\theta} dxdy \tag{3}$$

where γ_{sat} is the saturated density of slope layer, dxdy is the bottom area of micro-element body, θ is the slope angle of geology model.

Therefore, the component force of the saturated layer in x direction can be expressed as formula (4).

$$dG_x = \gamma_{sat} z tan\theta\, dxdy \tag{4}$$

Component force in z direction is seen formula (5)

$$dG_z = \gamma_{sat} z\, dxdy \tag{5}$$

The gravity dG_w of micro-element body

From the mechanical analysis, the gravity dG_w of the micro-element body can be expressed as formula (6).

$$dG_w = \gamma_{sat} dV \tag{6}$$

where dV is the volume of micro-element body, dV = dxdydz, dz is the thickness of micro- element body.

The gravity component in x direction of micro-element body is seen formula (7).

$$dG_{wx} = \gamma_{sat} sin\theta dV \tag{7}$$

The gravity component in z direction of micro-element body is seen formula (8).

$$dG_{wz} = \gamma_{sat} cos\theta dV \tag{8}$$

Seepage flow $\mathrm{dF_1}$

The seepage flow $\mathrm{dF_1}$ in x direction of micro-element body is seen formula (9).

$$dF_1 = \gamma_w j dV \tag{9}$$

where γ_w is water density, j is hydraulic gradient,$\mathrm{j} = \Delta\mathrm{h}/\Delta\mathrm{L}$, Δh is water head difference or head loss, ΔL is seepage path, $\Delta\mathrm{h} = \Delta\mathrm{z} + \Delta\mathrm{p}/\gamma_\mathrm{w} + (\Delta\mathrm{u})^2/2\mathrm{g}$, Δz is the position head difference, $\Delta\mathrm{p}/\gamma_\mathrm{w}$ is pressure head difference, $(\Delta\mathrm{u})^2/2\mathrm{g}$ is flow velocity head difference. On considering of low flow velocity in saturated layer, set the flow velocity head difference minimum. Another point is micro-element body is parallel with slope debris layer, then presume the water pressure in upstream slide is equal to the downstream slide, thus neglect the water pressure head. dV is the volume of micro-element body. Therefore, the formula (9) can be set as formula (10).

$$dF_1 = \gamma_w sin\theta dxdydz \tag{10}$$

Shear resistant $\mathrm{d}\tau_\mathrm{r}$ among particles

During seepage process, the particle framework prevents the water flow across the porosity among the particles. It set the framework as high dense of debris, and then at random depth of z, the shear resistant among particles can be expressed as formula (11).

$$d\tau_r = (\gamma_s - \gamma_w)(1 - n)\cos\theta\, dxdydz \tag{11}$$

where γ_s is soil particles density, n is porosity, θ is slope angle, dV is the volume of micro-element body,$\mathrm{dV} = \mathrm{dxdydz}$,dz is the thickness of micro-element body.

As formulas ahead, the dynamic force along slope direction is including seepage force and the gravity component, which can be expressed as the formula (12).

$$dF_d = \gamma_w sin\theta dxdydz + \gamma_{sat} z tan\theta\, dxdy + \gamma_{sat} sin\theta dxdydz \tag{12}$$

The force in z direction is mainly composed of gravity component, which is expressed as formula (13).

$$d\sigma = \gamma_{sat} z\, dxdy + \gamma_{sat} cos\theta dxdydz \tag{13}$$

The pore water pressure is seen formula (14)

$$dp = \gamma_w z\, dxdy \tag{14}$$

Combined with the Mohr-Coulomb criterion, the resistant formula in x direction of micro-element body can be expressed by formula (15).

$$dR = c + (d\sigma - dp)\tan\varphi + d\tau_r \tag{15}$$

Therefore, the formula (12) and (15) are the dynamic expression and resistance expression respectively, which locate at the depth of z and the saturated seepage flow in the whole layers. Among it, formula (12) is constitute of seepage force, the gravity component of soil in x direction and the micro-element gravity component. Formula (15) is mainly composed of cohesion, friction in deposit layer and the shear resistant among the particle.

From those two formulas, it can get the stress distribution of the micro-element body under saturated seepage flow of the dynamic and resistance vertical in slope direction respectively. From the formula (12) and (15), the dynamic force and the resistance varied with slope angle, soil strength and porosity of layer et. cl. The depth z is the variable, the micro-element body thickness is dz, it assumes the micro-element thickness is the characteristics particle size d_{50} of the deposit layer, it also grants the bottom area of micro-element is dA = dxdy = 1, therefore, the dynamic formula and the resistance formula can be expressed as formula (16) and (17) as follows.

$$F_d = (\gamma_w + \gamma_{sat}) sin\theta d_{50} + \gamma_{sat} z tan\theta \quad (16)$$

$$R = c + [\gamma_{sat} cos\theta \tan\varphi + (\gamma_s - \gamma_w)(1-n)\cos\theta] d_{50} + (\gamma_{sat} - \gamma_w)\, z tan\,\varphi \quad (17)$$

The porosity and the density are constant when the slope layer is constituted of homogeneous isotropic particles. Thus, the dynamic force and the resistant varied in linear with depth in z direction. While the slope material is composed of heterogeneous particles, the density and the porosity changed with depth, thus the dynamic force and the resistant shown nonlinearity with depth in z direction. Therefore, take the homogeneous isotropic particle layer as example, set the parameters as seen in Table 2. It can get the force distribution map of dynamic and resistant along z direction under fixed condition, seen Fig. 3.

Table 2. The parameters of deposit under saturated seepage flow condition

Layer	Slop angle	θ	°	12
Deposition Particles	Porosity	n	-	0.3
	Characteristic particle size	d_{50}	mm	3
	Cohesion	c	kPa	0
	Internal friction angle	φ	°	30
	Particle density	γ_s	kN/m3	22.3
Saturated Seepage Flow	Water density	γ_w	kN/m3	10
	Saturated density	γ_{sat}	kN/m3	18.4
	Flow discharge	Q	ml/s	440

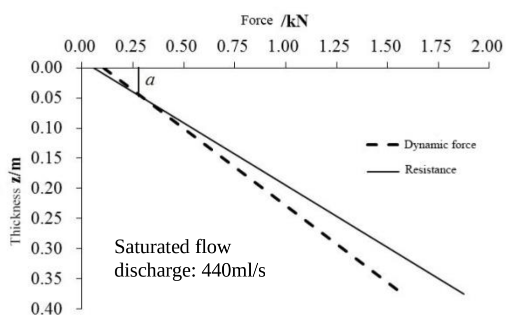

Fig. 3 The stress distribution of movable solid materials under saturated seepage flow

From Fig.3, the dynamic force and resistant of movable solid materials under saturated seepage flow show linear distribution, it also get that the critical thickness a of the homogenous layers is about 5 cm when the seepage flow discharge is 440 ml/s. Actually, with increasing of flow discharge, the critical movable thickness will exceed 5 cm, which will initiate more solid materials.

4. Discussion and Conclusions

4.1 Discussion

Actually, loosen solid materials initiated by rainfall and surface water has been researched widely (Takahashi, 2007), which classified as landslide transforming type and water erosion type. On considering with hydraulic theory, it set up dynamic force and resistant formulas in saturated seepage condition which mainly composed of gravity component and pore water pressure. Actually, pore water pressure is a variable parameter in different position and is difficult to obtain, because of the spatial location easily changing in the loosen materials layer during the failure process. Thus, the model posed in the paper is also need to be improved in the future research.

4.2 Conclusion

Water is one of the most essential compositions for debris-flow formation. The research posed a concept of the movable solid materials in mechanics firstly. Then take the contrast between the new concept and other traditional terms in definition, calculation method and mechanics meaning aspects, it easily got that the movable solid material whether move or not under hydrodynamic condition are a mechanical problem, rather than traditional definition and estimation. Thirdly, take saturated seepage flow as example, through built geology model and carried mechanical analysis, set up the dynamic force and resistant formulas in fixed condition, through set confined parameters, it got a liner distribution of the two formulas with depth increasing when the geology model is homogenous and the seepage flow saturated in whole deposit layer. The next step is to verify the formulas based on experiment and field observation.

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