

Conversion mechanism of gravelly soil to viscous debris flow

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Abstract A viscous debris flow is a mixture of gravelly soil and water. It consists of a slurry composed of small particles and water, with larger particles suspended in the slurry. Its structure force is smaller than that of gravelly soil. The process of gravelly soil changing into viscous debris flow may be divided into the filling water stage, the quasi-debris flow stage and the viscous debris flow stage. All stages have converting condition formula. The grain-size distribution of gravelly soil and the depositing shapes of gravelly soil also affect the conversion to viscous debris flow.

INTRODUCTION

Viscous debris flow is a common erosion phenomenon of slopes in mountain regions. Based on an analysis of some typical examples of viscous debris flow gullies in China, the formation of viscous debris flow is related to the regolith in its source area. In Jiangjia Gully, and Hunshui Gully in Yunnan Province, the grain-size distribution of source material is nearly the same as that of the viscous debris flow. The source material is gravelly, comprising clay, sand, gravel and water. Therefore, viscous debris flow develops from gravelly soil. Based on experimental studies and investigations, an analysis of the mechanism of gravelly soil developing into viscous debris flow provides a theoretical basis for formation, prevention and control measures of viscous debris flow.

THE MECHANICAL NATURE OF GRAVELLY MATERIAL AND VISCOUS DEBRIS FLOWS

The composition of gravelly soil and viscous debris flow

Gravelly soil is an aggregation of gravel, sand, clay, organic matter and water, with solid, liquid and gas components. Grains of soil and organic matter make up the solid part and form the skeleton of gravelly soil. The gas and liquid fill in the skeleton. The liquid part of gravelly soil is composed of water and dissolved matter in water.

Viscous debris flow differs from gravelly soil and is a dispersion

composed of gravels, grains of sand, a slurry constituted with grains of powder (0.05-0.005 mm), grains of clay (<0.005 mm), organic matter and water, and the water content is always in a supersaturated state, containing no or only a small proportion of gas.

Considering only the solid part of gravelly soil and viscous debris flow, the mechanical composition of viscous debris flow is nearly the same as that of the original gravelly soil that forms the viscous debris flow. This indicates that the mechanical composition of gravelly soil does not change when it becomes a viscous debris flow (Wu Jishan, 1981).

Omitting the effect of gases, the difference between gravelly soil and viscous debris flow is only a different proportion of solid and liquid in the total volume, i.e. the water content is different.

The structure of gravelly soil and viscous debris flow

In gravelly soil, the arrangement state, bond features, and pore features among small grains, large grains, and large and small grains determine the basic structure. The large grains accumulate freely under the action of gravity and form a loose macrostructure. The small grains form a net-like microstructure by molecular attraction and fill in the pores of the macrostructure. The small and large grains are in contact with each other. The water in gravelly soil exists in the states of bound water and pore water.

In viscous debris flow, gravels scatter in the slurry or sink to the bottom, and are enclosed by a mud film. The cohesive mud film is the binding layer among large grains. Sand particles in viscous debris flow are generally suspended by slurry, and are a part of the slurry. Grains of powder and clay mix with water and make up the mainly liquid part of viscous debris flow (Zhou Bifan, 1991). Therefore, the structure of viscous debris flow is completely different from that of gravelly soil.

The structure force of gravelly soil and viscous debris flow

The structure force of gravelly soil can be determined by the Coulomb formula:

$$s = c + \sigma \tan \varphi \quad (1)$$

where s = shear strength, c = cohesion, φ = angle of internal friction, σ = compressive stress.

The structure force of viscous debris flow can also be determined by the Coulomb formula.

Because of the different structure and water content of gravelly soil and viscous debris flow, the value of c is much smaller in viscous debris flow than

in gravelly soil. In addition, the weight of large grains is reduced by uplift of slurry and grains in the slurry are in a suspended state, so the value of σ is very small too. Therefore, it is clear that the structure force is much smaller in viscous debris flow than in gravelly soil.

The state of gravelly soil and viscous debris flow

With increasing water content, the state of soil can be changed from elastic, elastic-plastic, elastic-plastic-viscous, plastic-viscous to a viscous body (Komamura & Huang, 1974).

There is no consensus of opinion on the state of viscous debris flow. But it has been proved experimentally that its moving state is changed by a change of shear stress (τ). The author holds that viscous debris flow belongs to a transitional category between a soil body and a viscous body and accords with the rheological pattern of a Bingham body.

THE PROCESSES OF GRAVELLY SOIL CONVERSION TO VISCOUS DEBRIS FLOW

The converting mechanism of gravelly soil to viscous debris flow includes the action of both internal and external forces. Surface flows are an external cause and soil landslides and collapses are internal causes. The initial state of viscous debris flow caused by rainfall is due to the action of external force in the main and its later stage is due to the action of internal force. The conversion process must include mixing and is shown by Fig. 1.

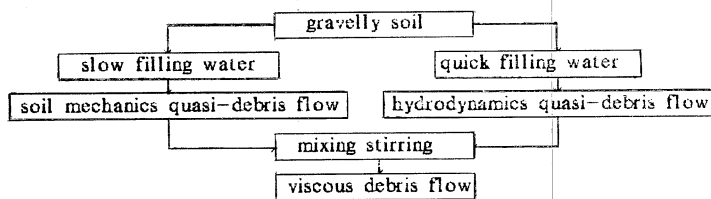


Fig. 1 Block diagram of the processes of gravelly soil conversion to viscous debris flow.

The filling water process of gravelly soil

In the formation area of a debris flow, there are large amounts of loose gravelly soil deposited on a hillslope with a certain gradient. For small water contents, gravelly soil on the hillslope is in a stable state. With the action of underground and surface water, the water content of the gravelly soil is increased, and when the water content reaches a certain value, the angle of

internal friction (φ) and the cohesion (c) decrease, the strength of gravelly soil is decreased and the gravelly soil changes into a critical state. This process is called the filling water process.

The filling water process contains quick filling and slow filling water. The slow filling water is a result of runoff of underground water and permeating surface water and progressively increases the water content of gravelly soil. The quick filling water means the water content increases quickly due mainly to surface flow caused by heavy rainfall.

The quasi-debris flow process

The definition of quasi-debris flow The quasi-debris flow, composed of loose materials caused by hillslope erosion and gravitational erosion, is a kind of transition body between gravelly soil and viscous debris flow and its mechanical nature is neither different from the original soil nor different from the viscous debris flow. It develops from the gravelly soil moved along a hillslope after the filling water process. Because the initiation of soil movement is affected by internal and external forces, quasi-debris flow can be divided into soil mechanics quasi-debris flow and hydrodynamics quasi-debris flow. Soil mechanics quasi-debris flow is mainly caused by internal force of soil and hydrodynamics quasi-debris flow is chiefly a result of the erosion effect of water or slurry on soil.

The forming processes of soil mechanics quasi-debris flow When soil is in an unstable state, its internal structure is destroyed and soil starts to move. The pattern of movement varies with changes in the strength of the soil structure and changes in the gradient of the slope and gully. Some patterns of movement are as follows.

- (a) *Wriggling process*: Soil moves slowly along a slope with an unchanged gradient under the uniform conditions of filling water and soil structure.
- (b) *Wriggling-disturbance process*: The slowly moving soil body suddenly moves faster because supplies of water and soil abruptly increase, the soil has a nonuniform structure or a gentle slope becomes a steep slope.
- (c) *Wriggling-collapse process*: Soil in the wriggling state collapses and slides down as the gradient of a slope suddenly steepens.
- (d) *Collapse-disturbance process*: Due to a nonuniform filling water process and soil structure, first the front part of the soil collapses and slides down, then the rear part moves quickly in a state of disturbance.
- (e) *Collapse, slide process*: Lumps of soil suddenly start to move quickly on a hillslope with a certain gradient.

The forming process of hydrodynamics quasi-debris flow A soil body moves fast with quick filling water; water or slurry and soil generally leave each other in moving and slurry or water as transporting medium carries soil

body. This is because the water flow caused by rainfall or snowmelt moves fast and erodes the soil. The process can be described as water flow/slurry flow/quasi-debris flow or water flow/quasi-debris flow.

The viscous debris flow process

Both a hydrodynamic quasi-debris flow and a soil mechanics quasi-debris flow will converge in a ravine after moving some distance. Then there are two possible cases: one is deposition due to an inadequate supply of quasi-debris flow or because of a gentle slope, and the other is continued movement. After some time, the latter makes the two types of quasi-debris flow mix together completely. When they run out of the formation area, the quasi-debris flow has become viscous debris flow.

THE CONDITIONS FOR CONVERTING GRAVELLY SOIL TO VISCIOUS DEBRIS FLOW

The background conditions

Grain-size distribution in gravelly soil The content of gravel, sand and clay and their grain-size distribution can determine whether or not a gravelly soil changes into a viscous debris flow. If the density of a debris flow is over 1.8 t m^{-3} , when the clay content is more than 5%, the debris flow is converted from a gravelly soil to a viscous debris flow; when the clay content is from 3% to 5%, it becomes a transitional debris flow (Li Jian & Zhong Dengleng, 1989). If the density of a debris flow is below 1.8 t m^{-3} , when the clay content is too high, it forms a muddy flow or dilute debris flow, when the clay content is too low, it becomes a dilute debris flow or water-stone flow. If the sand content is too low or the gravel too low, it generally forms a water-stone flow or dilute debris flow (Table 1). Therefore, the grain-size distribution plays an important role in gravelly soil changing to viscous debris flow. According to grain-size distribution data of the source soil and viscous debris flows from typical viscous debris flow gullies in China, the favourable distribution ranges for viscous soil to convert to viscous debris flow are: $>2 \text{ mm}$, 55-70%; $2-0.05 \text{ mm}$, 15-25%; $0.05-0.005 \text{ mm}$, 5-15%; $<0.005 \text{ mm}$, 5-10%.

Table 1 Relationship between fluid type and grain-size distribution.

Type	Gully	Grain-size distribution (%):			
		$>2 \text{ mm}$	$2-0.05 \text{ mm}$	$0.05-0.005 \text{ mm}$	$<0.005 \text{ mm}$
Flood	Jiangjia	0	3.50	44.50	52.00
Dilute debris flow	Jiangjia	74.20	17.03	3.23	3.54
Transitional debris flow	Hunshui	55.80	34.60	5.60	4.00
Viscous debris flow	Yinda	60.10	22.02	11.04	8.64

Slope shape accumulated by gravelly soil The accumulated shape of gravelly soil can be divided into steep slope and gentle slope. On steep slopes, the action of the gravitational force along the slope is stronger and the gravelly soil is easy to start and forms a soil mechanics quasi-debris flow. On gentle slopes, the gravitational force on the soil is weaker and the possibility of inducing landslide and collapse is smaller, but the line groove or cut groove can be formed easily due to surface flow erosion and it is possible for gravelly soil to start moving. Therefore, hydrodynamic quasi-debris flow can be caused easily on gentle slopes.

It is easy for landslides or collapse to be induced on steep slopes and to provide large amounts of solid matter. But on steep slopes the landslide and collapse processes are shorter and the distance moved by the soil is also shorter, so soil and water have less chance to mix. If the mixing and stirring process is not completed, the soil and water will disperse and the soil only can change into quasi-debris flow, not into viscous debris flow.

On gentle slopes the action of gravity along the slope is weak. If an external force causes gravelly soil to start moving, but the velocity is slow, it will stop on the gentle slope after a short time. When quasi-debris flows come together in a gully bed of forming area, if the slope of the gully bed is too small, it will stop. If the slope is too steep or length of gully bed is too short, the quasi-debris flow will run out of the forming area at once, and the gully bed of the forming area will lose its capacity for the quasi-debris flow to mix and stir. Therefore, the conversion of gravelly soil to viscous debris flow will occur only for a certain range of slopes. For slopes outside this range, the soil will become transitional or dilute debris flow.

The favourable ranges of slope for gravelly soil to turn to viscous debris flow may be: gentle (20-25°), steep (30-40°) and the slope of gully bed of forming area, 12-15°.

The mechanical conditions involved in gravelly soil to viscous debris flow

The converting conditions of filling water process Whether by slow filling or quick filling water process, the function of water is to make gravelly soil turn to quasi-debris flow. In the filling water process, the water content of the soil would determine the converting condition. The critical content includes both the filling water volume (R_f) and water content (P_a) of the soil before filling with water. If only rainfall is considered as the water source for the filling water process in a debris flow gully, the water volume (R_f) can be determined by:

$$R_f = \sum_{t_o}^{t_n} (r - u) \quad (2)$$

where, t_o is the starting time of the rainfall, t_n is finishing time of the filling water process, r is rainfall intensity, and u is infiltration loss of rainfall.

The water content of soil before filling with water can be determined by

taking samples of the soil. For convenience of calculation, it may be replaced approximately by the amount of precipitation before the filling water process, so:

$$P_a = P_1K + P_2K^2 + P_3K^3 + \dots + P_nK^n \quad (3)$$

where $P_1, P_2, P_3, \dots, P_n$ are daily precipitation values (mm) from the first day to n days before the debris flow, and K is a coefficient of progressive decrease; generally $K = 0.8$.

Therefore, the necessary condition for the filling water process is:

$$R_t + P_a > W_L \quad (4)$$

that is:

$$W > W_L \quad (5)$$

where W_L is the water content of liquid limit of gravelly soil.

The converting conditions of quasi-debris flow process Figure 2 shows a typical pattern of soil mechanics and hydrodynamics quasi-debris flows.

With the type I, the resistance (τ_r) and the element of gravity (τ_x) of a soil body along the slope can be determined by:

$$\tau_r = c + \sigma \tan \varphi = c + r_s H \cos^2 \theta \tan \varphi \quad (6)$$

$$\tau_x = W \sin \theta = r_s H \sin \theta \cos \theta \quad (7)$$

When $\tau_x - \tau_r > 0$, then:

$$\tan \theta - \tan \varphi - c/r_s H \cos^2 \theta > 0 \quad (8)$$

This is the converting condition formula for a soil mechanics quasi-debris flow.

With type II, the weight of a soil body (W) and seepage force of water (F) can be given by:

$$W = h \cdot r' = (r - r_w)h \quad (9)$$

$$F = (h_o + h)r_w \sin \theta \quad (10)$$

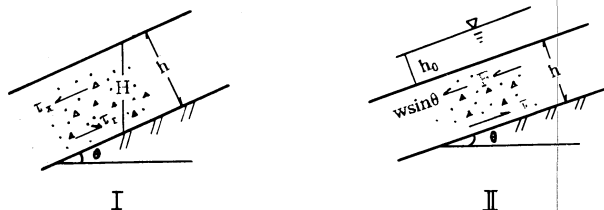


Fig. 2 Mechanical pattern of converting quasi-debris flow.

where, r' is the buoyant weight, r , the unit weight of saturated soil.

The converting condition of hydrodynamics quasi-debris flow can be determined by:

$$W \sin \theta + F > c + W \cos \theta \tan \varphi \tag{11}$$

that is:

$$rh + r_w h_o - c / \sin \theta - h(r - r_w) \tan \varphi / \tan \theta > 0 \tag{12}$$

The converting conditions of the viscous debris flow process Viscous debris flow must overcome the resistance in moving. The resistance on a unit area (τ) includes two parts: the moving friction resistance of the soil body (τ_s), and the friction resistance of the liquid body (τ_w) (Fig. 3), so $\tau = \tau_s + \tau_w$. τ_s and τ_w can be determined by the following formulae:

$$\tau_s = \sigma_y \tan \varphi \tag{13}$$

$$\tau_w = \tau_y + \mu \cdot dv/dh \tag{14}$$

where τ_y is the yield stress of the liquid body; μ , the dynamic viscosity coefficient; dv , the velocity difference of nearly liquid layers; dh , the vertical distance of nearly liquid layers.

If the surface and bottom layers of viscous debris flow are considered as nearly two layers, the velocity difference is surface velocity (V), and vertical distance is flow depth (h). In the critical state of viscous debris flow to convert, the surface velocity is zero ($V = 0$). Therefore, the resistance of viscous debris flow in the critical state can be determined by $\tau = \tau_s + \tau_y$.

In viscous debris flow, grains of clay smaller than 0.05 mm mix with water to form a slurry. The slurry can suspend larger grains. The maximum diameter of suspended grains may be calculated as (Qian Ling & Wang Zhouyin, 1984):

$$D_o = 60\tau_y / (r_s - r_m) \tag{15}$$

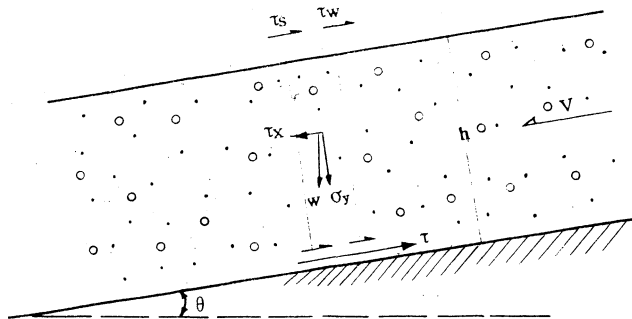


Fig. 3 Converting pattern from quasi-debris flow to viscous debris flow.

where, r_m is unit weight of slurry composed of grains below 0.05 mm with water.

Grains smaller than D_o form part of the slurry in viscous debris flow. They increase the yield stress of the slurry, but do not produce the friction resistance of a soil body. Therefore, in viscous debris flow, the weight of the soil body must remove these weights. The loss weight is: $V_s P_o r_s$, where P_o is the weight percentage of grains under D_o in the soil body, V_s is the total volume of the soil body, r_s is the unit weight of the soil.

Grains larger than D_o are uplifted by the slurry and their weight will be lightened. The loss weight is: $r_m V_s (1 - P_o)$, where r_m is unit weight of slurry composed of grains smaller than D_o with water in debris flow.

Therefore, the effective weight of the soil body in viscous debris flow is:

$$W = V_s r_s - V_s r_s P_o - V_s r_m (1 - P_o) \quad (16)$$

that is:

$$W = (r_s - r_m)(1 - P_o)V_s \quad (17)$$

Viscous debris flow only moves due to shear force of soil along slope. A shear force, provided by the soil body, over or equal to the moving resistance is necessary for viscous debris flow to occur, so:

$$C_v h r_s \sin \theta > \tau_s + \tau_y \quad (18)$$

In formula (18), C_v is the volume content of solid material. Therefore:

$$C_v h r_s \sin \theta > \tau_y + C_v h (r_s - r_m)(1 - P_o) \cos \theta \tan \varphi \quad (19)$$

$$\tan \theta > \tau_y / C_v h r_s \cos \theta + (r_s - r_m)(1 - P_o) \tan \varphi / r_s \quad (20)$$

From formula (20), we can know that viscous debris flow will move when the angle of slope is above a certain value. The critical value of this angle depends on the composition properties (r_s , r_m , P_o , C_v , φ , τ_y) and depth of debris flow.

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