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Review on depositional behavior of viscous debris flow

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Abstract—**Viscous debris flow characterized as high density, ranged from clay to meters boulders and destroyed seriously. Due to disaster always emerged on the deposit process, so this paper began with a survey of literature on deposit process and depositional characteristic of viscous debris flow. By reviewing on the theory model, deposit process and depositional characteristic combined with experiment and field work, found that theory models were too simple to use in natural debris flow. Modeling always ignored some important characteristics, such as scaling effect, boundary effect, time effect, etc. Experiment research also rather limited and can't consider scale and boundary effect very well. Field work was the only way to recognize the physical feature of debris flow, and it's very necessary to improve the quality and quantity of the data available in the next work. Reveal the deposition mechanism from a single surge model was proposed to build, which will consider both interstitial flow and coarse granular. Based on real topography, the simulation result will have practical significance in forecasting deposition area and destroy degree in some way.**

Keywords—**viscous debris flow, deposition characteristic**

I. Introduction

Since the beginning of 20th century, debris flow began to be noticed, and until the 1960s scientists began to investigate the mechanisms of debris flow. The most comprehensive and detailed observations and mathematical-physical studies have been conducted in Japan and China (Huttcr, 1996), especially in field observing and experiment research. Under plenty of natural disasters threaten, research work is operated and processed gradually. An (2011) researched current state of landslide and debris flow by SCIE papers included on Thomson Data Analyzer(TDA) and Ucinet from 1902-2010, the results show that there emerged lots of papers about geological disaster since 1991 and several developed countries have greater contribution on this field; GIS, tsunami, numerical simulation and submarine landslide are new topics in recent 10 years; modeling always is main method to study geological disaster. It is very clear that International Decade for Natural Disaster Reduction promotes the research of debris flow and landslide effectively, and there also emerge a great deal of achievements.

Despite predecessors have done many significant works in different views and widespread recognition of the uniquefeatures of debris flow deposits, the value of mechanistic interpretations of the depositional process has remained dubious. Topography is one of main factors and directly controls the flow state and deposition behavior. Hübl (2011) simulated two viscous debris flows by FLO-2D computer model on the basis of topographic data, observation and flow parameters which was tested by a rotational viscometer, but the calculated results had some differences with the natural debris flow. Boulder is agreed with the most important factor to cause disaster, however, what force supports it to move on the deposition fan far from the mouth of valley is always an obscure problem. Cohesive strength, buoyancy and dispersive stress of debris flow are regarded as the main forces, but Davies (1986) concluded that both cohesive strength and buoyancy can't support grain to move and only if the shearing of grains in the inter-granular slurry is viscous, dispersive stress will carry larger material. Kinds of factors are considered by different researchers due to complexity and available of research, which are velocity, depth, concentration, clay content and coarse particles, discharge, friction angle, yield stress, etc., and the yield stress or the basal friction angle are considered to govern the depositional behavior to a large extent (Rickenmann, 2006).

In the beginning of 21th century, several large earthquakes which usually led to seriously secondary geo-hazard, such as Wenchuan Earthquake, Ms=8.0; Chili Earthquake, Ms=8.8 and Japan Earthquake, Ms=9.0, make kinds of fields researchers pay attention to the importance of geological disaster again. China is a mountain-rich developing country, due to complicated tectonic landform, which geological disaster is rather seriously and frequently, especially after Wenchuan Earthquake in 2008. Lots of geological disaster frequently occurred in the western of China, such as Yushu Earthquake and Zhouqu Debris-flow in 2010, Ya'an Earthquake in 2013, and it maybe demonstrate the Himalaya activity gradually. Summarizing existed research to help people have a better recognize to essential phenomenon. The essential problem and main contradiction will be revealed and convenient to explore research systematic further. So this paper begins with a survey of literature on deposit process and depositional characteristic of viscous debris flow to help people understand how to prevent and mitigate disaster better in natural debris flow.

II. Deposit process

Generally, viscous debris flow behaviors as intermittent flow, which contains as many as hundreds of surges and will last several minutes to decades of hours. The mean velocity is 8-9m/s, and sometimes can up to15m/s or more (Browning, 1970). The deposit process is the process of emerging disaster actually, such as bury, impact, block river, etc. Viscous debris flow usually stops to deposit due to terrain change, water and debris in short supply. Existed hypos model think that a slipping rigid body will decelerate and finally stop when the kinetic friction force becomes larger than the gravitational driving force. In general, the kinetic friction coefficient is 0.6 with a decreasing slope gradient motion stops. But the natural debris flow can move on a slope as flat as 3°. Takahashi (2007) agreed that there was some kind of lubrication mechanism to lessen the apparent kinetic friction coefficient.

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A. Deposition model

a) Visco-plastic model

It may be more reasonably to consider debris flow as a non-Newtonian fluid, which obviously behaves differently to plain water flow. There are two visco-plastic models which constitutive equations are as following:

Bingham fluid: τ = τy + η(du/dz) (1)

Herschel–Bulkley fluid : τ = τy + K1(du/dz)n, n ≤ 1 (2)

where, τ is shear stress; τy is the yield stress (strength); (du/dz) is the rate of strain, η is the rigidity modulus or the viscosity of Bingham fluid.

Bingham visco-plastic model, which thinks that the debris flow has uniform intrinsic shear strengths and that deposition occurs if the intrinsic shear strength exceeds the gravitational driving stress, is also the most often used one for the shear rate range seen in natural rivers and on alluvial fans. The value of τy and η, which are influenced by mixture, solid concentration and temperature, are obtained from field work to apply Bingham fluid model. Although many tests have been done in kinds of different scales debris flows, it still can't get available parameter due to rheometer can't to use in coarse particles flow in particular boulders diameter greater than 1 m. Theory research and field investigate showed there was a plug in velocity profile, which velocity is different from near-surface velocity. But typical viscous debris flow in the Jiangjia ravine of China lacked the plug that should exist in a viscoplastic fluid flow (Takahashi, 2007).

Bingham models of debris flows have almost invariably assumed fixed viscosities and yield strengths and momentum transport and energy dissipation in debris flows occurs exclusively by viscous shearing. It also has some significant limitations in application and neglects the fact that rate-independent energy dissipation can occur when sediment grains contact one another or flow boundaries, and also neglects fluid flow relative to the granular assemblage. Wan (1982) agreed that Bingham model may overestimate the true yield stress due to the shear thinning at low shear rates. The application in practical projects remains to be discussed.

The HB model also was found to be generally valid for muddy-type debris flow materials where the fine fraction (particle size less than 40 mm) is greater than 10% to lubricate contacts between grains (Coussot,1994). Rickman (2006) considered one phase for the computation of the unconfined free-surface spreading of visco-plastic materials based on the conservative form of the steep-slope shallow water equations which are solved using a finite volume technique on a rectangular grid. The results showed HB model was sensitive to peak discharge and site-specific field topography played an important role in simulation. It is found to fit rheological data very well over a wide range of shear rates.

b) Bagnold model

Debris flow behaves as collisional grain flow which first studied by Bagnold(1954) in continuous flow of sand grains, this model assumed that deposition occurs if resistance due to grain-collision stresses surpassed gravitational driving stress. The constitutive equation is

$$\tau = a(du/dy)^2 \qquad (4)$$

where, proportional coefficient a was influenced by solid concentration and particle size.

Bagnold's simple theoretical considerations are based on a regular array of identical hard spheres and thus could not create size grading under rapid shearing motion, which is one mechanism that gives rise to dispersive pressure (Hutter, 1994; Pasquarell, 1988). The model only used for particles of constant size and may not be applicable to mixed grain sizes (Lemieux, 2000). Modeling the non-newtonian behavior of debris flows in Japan relies almost exclusively on Bagnold's dilatant fluid model (Huttcr, 1996). Takahashi (1978) suggested that the main characteristics of debris flow would be produced by the frequent collisions between coarse particles, and the effect of interstitial fluid would be negligibly small. Caution should be exercised against the use of Bagnold's model before the inconsistencies are completely resolved.

B. Destroy behavior

The deposition area always lived as a political, economy and culture center in developing countries, particularly such as in the southwest of China. The typical characteristics of these areas are population density is large and vital traffic lines cross these areas. Once debris flow broke out in these areas, disaster will be inevitable. Series of disaster patterns are paid more and more attention, which are bury, impact, block river, etc.

a) Bury

Viscous debris flow will cover and bury everything, such as farmland, houses, highway and railway, etc., along the flow path. The bury behavior began from debris flow rushed out the mouth of gully until the velocity of debris flow decreased to zero. This process commonly takes several seconds or minutes depend on flow velocity, discharge and the gradient of deposition area. Bury caused people can't breathe and rescue was very hard to operate because of high density and viscous, which also caused farmland area decreased and stone-landification. According to incompletely statistic, there are as many as 1.2×10^6hm^2 farmlands threaten by debris flow in China (Kang, 2004).

b) Impact

Debris flow buried all of weak and small objects along flow path, and it would behave large impact force when it ran into big barriers, such as house, buildings. The impact force is regarded as the main destroy force results in disaster. Existed research stated that the impact force is composed by hydrodynamic pressure and impact force of boulders. Major(1997) found that bed friction concentrated along the flow perimeter results in debris-flow deposition and focused frictional resistance can enhance if margins are composed predominantly of coarse clasts. It is very clearly that impact force can lead to seriously disaster, but the destroy mechanism remains unclear presently.

c) Block river

Most of viscous debris flows, which are large-scale and composed of multi-surges, can move very far and finally rush into river. Compared to river, if velocity, discharge and density of viscous debris flow enough large it will form temporary dam very easily. The dam exists initiation dangerous and it can wash out the downstream and aggravate disaster further. In 2010, Zhouqu debris flow blocked Bailong River and produced a temporary debris-dam (Tang, 2011). The angle between flow direction and river was proposed an important factor, when angle closed to 90° it can block river more easily.

Besides above deposition behaviors, debris flow always destroys life-lines project, such as facilities of water, electricity and communication, and these make people life worse in disaster area after disaster. Debris flow also threats the industrial and agricultural development seriously.

III. Deposit characteristic

Deposition is the finally product of debris flow, and study debris-flow fan is useful for gaining insight into the spatial and temporal patterns of deposition because fans preserve a record of past events that can be interpreted from their deposition characteristics.

A. Morphological characteristics

The essential morphological characteristics of deposition fan are controlled by the topography of buffer and mechanism of debris flow motion and deposition. Most fans are elongated or tongue-like that has a dense interior structure, some is ring structure or strip-like. The deposit margin is steep (49°-57°) and convex and appears to be formed by high-viscous debris flows with generally higher internal shear strengths. The scale of deposition fan is 0.8-3km^2 and depends on the buffer scale and debris flow discharge.

In frequently debris flow area, deposition fan is formed by many times debris flow and it never stands for a single debris flow characteristic (Li, 2004). The thickness of deposition fan also is one of main characteristics, which ranges from centimeters to meters. The boundary thickness is clearly thicker than the inertial in the lateral profile and the frontal thicker than the tail in the longitudinal. Kokelaar (1996) suggested that deposit thickness and shape merely reflect deposit strength, which is greatly influenced by sediment permeability, pore-fluid pressure, and frictional strength along deposit margins (Major, 1997), when deposition is dominated by vertical accretion, the resulting deposit thickness has little bearing on flow strength. Major emphasized that deposit thickness cannot be used to infer the strength of flowing debris, because deposition usually forms by several surges and results from frictional resistance focused at flow margins.

There are some micro-morphology on the surface of deposition fan, such as lobe, snout, levee, debris dam and channel. Lobe squeezed out from the main flow direction and formed a blunt margin or overlaps on the surface of deposition fan. The scale is very small and the thickness can be estimated the velocity and strength of single surge. Snout is formed by the fontal of a single surge and regarded as the main constitute in disaster, which marks the farthest distance of single surge reached to and looks like a stony-rich higher wall. Due to the kinetic sieving mechanism quickly elevated through the surrounding smaller particles to the surface layer, indicating that deposition results mainly from resistance at flow heads and margins. Coarse material is accumulated at the front of the surge(Di, 2003) generally has little or no pore fluid pressure and where the finer-grained tails of surges are nearly liquefied by high fluid pressure, which persists owing to the great compressibility and moderate permeability of the debris (Iverson,2005).

B. Stratification features

Profile of deposition fan usually showed less sorting mud-gravel structure, which is mud-wrap-gravel or gravel-clamp-mud phenomenon. Clear stratification features also are observed by researchers in deposition profile. Distinguish and understand stratification features can help us analyze the internal action of viscous debris flow deposition mechanism. There are five different layers observed in field survey and experiment test (Tang, 1990; Wang, 2003).

a) Normal grading

Grains deposit in normal order, with coarse gravels or boulders subsidizing before the smaller ones. The bigger granules have larger mass and sink gradually and sediment leads to graded layer due to gravitational differentiation of debris flow. The thickness of this kind of layer is more than 50 cm and the distribution difference is large in viscous debris flow interior.

b) Disorderly grading

It is mostly the graded bedding structure formed by viscous debris flow. Grains of various diameters are randomly distributed and poorly sorted due to drag force. This typical characteristic of viscous debris flow was formed when the particles were kept current nuclear and can't be sheared. Major emphasized that such homogeneous internal textures could be misinterpreted as the result of en masse emplacement by a single surge. This kind of disorderly grading is very common in viscous debris flow.

c) Inverse grading

In gravity driven shear flows with a free surface it is observed that the fine particles collect at the lower parts of the layer, whereas the largest particles move towards the free surface (Huttcr, 1996). Inverse grading involves an upward increase in either or both of clast size and percentage. Many studied exhibit inverse grading of their coarsest fragments in their research (Tang, 1990; Wang, 2003; Costa, 1981; Major 1986). The inversely graded bedding structure is usually found in debris flow deposits in China and lahar deposits in America and Japan. This uncommon phenomenon explained that the viscous interstial flow had special characteristic and can keep deposit from clay to boulder. It was first attempted to explain its physical property by Bagnold (1954) based on his "grain-inertia" theory. Middleton(1970) proposed a mechanism known as kinetic sieving, which is the process by small grains pass through the interstices between large particles when agitated, thus displacing the larger particles upward. Savage (1988) modified his theory and presented an analysis for flow of a binary mixture of small and large spherical particles of equal mass density down an inclined chute. Viscous debris flows possess high viscosity and yield strength; hence dispersive pressure, kinetic sieving, and fluid dynamic boundary effects are regarded as unsatisfactory mechanisms for inverse grading.

d) Rough grading

Rough grading which coarse sediment remains as fine particles in debris-flow deposit are swept away by flood. The surface layer becomes coarse and the gravels in this graded bedding structure distributed disorderly. Enos (1977), Major (1990) also observed this phenomenon in theirs research. A similar layer which called the gravel accumulated at surface was observed by Major in field experiment. It has similar characteristic with rough grading, but different with particles were vertical and the angle of gravel was 45°. According to analyze the observation data in field and large-flume experiment, Wang (2009) agreed that Weissenberg effect was the cause of formation mechanism of the gravels accumulated at surface.

e) Basal mud layer

Basal mud layer is a thin mud layer, consisting of clay and silt sands at the base of deposit. Tian (1985) inferred it was left when the first debris flow moved on surface of origin deposition fan at the beginning. It can reduce the friction force for later debris flow along deposition fan.

C. Particle characteristic of deposition

Viscous debris flow is composed of larger scale particles that commonly range in size from micrometers to meters and particle distribution isn't uniformity, and coarse particles up to 66%-92%. Research stated that the finer particle content between 3.75% and 7.50% is induced to initiate debris flow easily under the same rainfall and topography condition. The finer particles help sustain high pore pressures that reduce frictional resistance and enhance lobe spreading (Major, 1997). There are three types of solid particles in debris flow by particle size and physical-chemistry properties, which are coarse brecciated particle, finer sand particle and clay. Coarse brecciated particle is suspension-lapse state and sand is turbulent-support state, and the divided size is 4 mm; clay is coalescence and adhesion status and makes slurry generate normal stress, the divided size is 0.16 mm between sand and finer particles. This characteristic has essential difference with Newtonian fluid, which is 2mm and 0.005 mm, respectively. The particle distribution obeys Gaussian distribution and Rossing distribution, and the experiment results more close to Rossing distribution in coarse particles (Wang, 2001). The boulders distributed on deposition area disorderly, and this phenomenon was observed on most viscous debris flows in many countries. There is rarely reference for boulders motion and deposit mechanism. Boulders always led to the main flow skew toward the other directions on field investigation.

IV. Discussion

A. Phase type

Correct understanding on material physical properties is essential for studying its mechanism in debris flow. Debris flows behave more like non-linear, highly-viscous fluids at large strain rates. Due to both solid-like and fluid-like material behavior, debris flow belongs to what kind of material? This is always a controversy topic since humankind recognized debris flow phenomenon. The interstitial fluid, which was considered dispersed single phase rather than multiphase flows, plays an insignificant role in the transportation of momentum. Gas is usually ignored for whole material properties in soil mechanics, the same assumption as viscous debris flow. Han (2000) studied gas influence on viscous debris flow and proposed that gas can decrease the resistance during moving.

Natural debris flow behaves as a rigid body particularly on impacting process; but it will behave as a flexible body in the deposition process. Study debris flow as an outside-rigid and inside-flexibility material, which composed of solid, water and gas, appears to be a good way to close to natural debris flow.

B. Experiment

Laboratory experiment is very small and only several centimeters to meters and the test particle size usually less than 3cm and the channel is constant slope flume, which all ignored scaling effect and boundary effect. Viscous debris flow deposits typically are massive textured, poorly sorted, matrix-supported mixtures of sediment ranging in size from clay to boulders meters in diameter. Experiment is one of available ways to obtain parameters of debris flow, but how to use these parameters need to consider in practical projects.

Experiment just for exploring the debris flow feature but can't reproduce a real process, even sometimes misunderstand natural debris flow by some experiment phenomenon. No matter how large experiment is tested, it cannot replicable the natural debris flow either.

C. Field investigation and observation

Field observation is the most useful and directly way and plays a significant role in studying debris flow. It will record a real and clearly information to observe the flow state, deposition process, destroy behavior. By field investigation and observation, some characteristics of debris flow can be attained directly, such as deposition area, thickness, micro-morphology, particle distribution and destroy characteristic, etc. However, intermittent debris flow is the most important moving pattern of viscous debris flows. One debris flow incident always contains several surges, which often can be obtained by field investigation shortly after debris flow. It's worthwhile to pay more attention to measure characteristic parameters in field work and need to distinguish a single surge's characteristic with the whole incident's information on the basis of recognition of natural debris flow. Observe and investigate the characteristic of single debris flow is rather important besides the entirety feature and study it from a single surge to a complexity debris flow will be a good perspective. It's necessary to consider the surge shape's feature and further analysis on it how to influence the properties on debris flow.

Actually, observation only supplies transient information and its very limitation in the whole incident. It's not possible to record all of information as detailed as possible, due to deposition area is very large, and investigation is rough and ignore some details. Although the yield stress or the basal friction angle appeared to govern the depositional behavior to a large extent, the main factors and the deposition mechanism hasn't clear enough, assumption and evaluation seems necessary by empirical experience. The test equipment also is important and accuracy equipment can guarantee the precision information. It's very necessary to improve the quality and quantity of the data available in the next work.

D. Numerical simulation

A number of models were developed to simulate the debris flow due to the complexity of the debris flow. Simplified models appear to be a reasonable first step towards a systematic application and evaluation of simulation models. However, overly simplified model will lost reality. Debris flow is a multi-phases mixture essentially, both solid phase and fluid phase should be considered together. Due to scaling effect and flow isn't Newtonian flow, it's very difficult in building appropriate constitutive equations.

Debris flow behavior typically is influenced by inertial forces and by a combination of grain friction, grain collisions, and viscous fluid flow. Investigations of these influences indicate that traditional Bingham and Bagnold models of debris behavior should be supplanted by models that account for interactions of solid and fluid constituents. Empirical model should connect with the basic theory. Realistic models of debris flow physics need to account for these phenomenon which are grains visible on the surface of debris flows may either jostle energetically or lock together to form an apparently rigid plug, depending on the granular temperature, which in turn depends on flow speed, composition and boundary conditions.

In computer simulation, different models are available, one must find out what characteristic relation between the operating shear stress and the velocity of deformation exists in the particular flow about which one is talking. If the number of particles becomes large, the load on the computer becomes enormous. The quantitative macro characteristics of flow such as depth and velocity can be obtained only after the completion of simulation. At present, the continuum mixture theory that divides the constituent into the continuum solid phase and the continuum fluid phase taking the interaction between the phases strongly into account is the most influential.

One of the thorniest problems in the mechanics of granular materials is the prescription of boundary conditions. Complexity topography boundary condition usually makes flow direction vacillate and skew mainstream direction result in different deposition fan. Confirm the accuracy flow direction is the essential problem in simulation. The flow direction always variable on deposition fan, analyzing the boulders distribution may be a good try to check the flow direction. Combine accurate description of natural debris flow and fan topography is an effective way to achieve a good replication of the observed deposition pattern. N

It is also perhaps worth mentioning that no model appears sufficiently general to deal with processes such as deposition of sediment (Huttcr, 1996). Such processes are governed predominantly by turbulence in the fluid and agitation of the solid particles at the base of the flow. Consequently, these processes cannot be left out of any model hoping to address deposition. Further work to expand upon these models and include the effects of solid-fluid interactions is desirable.

V. Conclusion

As can be seen from the depth and breadth of research topics described in the previous section, there are still many aspects hasn't a systematic theory. Viscous debris flow is the most complexity and destructive debris flow and of which characteristic has big difference with mud-debris flow and stony debris flow. Scaling effect, boundary effect and time effect are needed to consider in viscous debris flow. It's available to simulate on real topography which can get easily because of developed satellite system.

References

An P.J., Li L., Zhang Z.Q. A bibliometrical analysis of international landslide research. *Advances in Earth Science*, 2011, 26(10): 1116-1124. (in chinese)

Bagnold R.A. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear: *Proc. R. Soc. London*, 1954, 225: 49-63.

Browning J.M. Catastrophic rock slide, mount Huascaran, North-Central Peru. *The American association of petroleum geologists bull*, 1973, 57 (7): 1335-1341

Coussot P. Steady, laminar, flow of concentrated mud suspensions in open channel. *Journal of hydraulic research*, 1994, 32(4): 535-559.

Davies T.R.H. Large debris flow: a macro-viscous phenomenon. *Acta mechanica*, 1986, 63:161-178.

Davies T.R.H. Debris-flow surges-experimental simulation. *Journal of hydrology*, 1990,29(1):18-46.

Enos P. Flow regimes of debris flow. Sedimentology, 1977, 24(1): 133-142.

Han W.L., Wang Y.Y., Zhan Q.D. Explore on gas reduce resistance in debris flow-Jiangjia ravine, Yunnan. *Journal of sediment research*, 2000, 5. (in chinese)

Huang X., Garcia M.H. A Herschel-Bulkley model for mud flow down a slope. *Journal of fluid mechanics*, 1998, 374:305-333

Hutchinson J.N. A sliding-consolidation model for flow slides. Canadian geotechnical journal, 1986, 23:115-126.

Hutter K., Rajagopal K.R. On flows of granular materials. *Continuum mechanics and thermodynamics*, 1994, 6:81-139.

Huttcr K., Svendsen B., Rickenmann D. Debris flow modeling: a review. *Continuum mechanics and thermodynamics*, 1996, 8:1-35

Hübl J., Steinwendtner H. Two-dimensional simulation of two viscous debris flows in Austria. *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science*, 2001, 26(9): 639-644.

verson R.M. Debris-flow mechanics. *Debris-flow hazards and related phenomena*, 2005, 105-134.

Kang Z.C. Topographic change in the stream channel by viscous debris flow. *Annuals of disaster prevention research institution*, Kyoto University, 1997, 40:167-172

Lemieux P.A., Durian D.J. From avalanches to fluid flow: a continuous picture of grain dynamics down a heap. *Physical review letters*, 2000, 85(20):4273-4276.

Major J.J. Experimental Studies of Deposition at a Debris Flow Flume. *USGS Open-field report*: 1990, 0-28.

Major J.J. Depositional processes in large-scale debris-flow experiments. *The journal of geology*, 1997, 105:345-366.

Middleton G.V. Experimental studies related to problem of flysch sedimentation. *Flysch sedimentology in North America*, 1970, 253-272.

Pasquarell G.C., Shen H.H., Hopkins M.A. Collisional stress in granular flows: Bagnold revisited. *Journal of engineering mechanics-ASCE*, 1988, 114:49-64.

Prior D.B., Bornhold B.D., Johns M.W. Depositional characteristics of a submarine debris flow. *The Journal of Geology*, 1984, 92 (6):707-727.

Rickenmann D., Laiglec D., McArdella B.W., etc. Comparison of 2D debris-flow simulation models with field events. *Computational Geosciences*, 2006, 10:241-264

Savage S.B., Lun C.K.K. Particle size segregation in inclined chute flow of dry cohesionless granular solids. *Journal of fluid mechanics*, 1988, 189: 311-335.

Takahashi T. Mechanical characteristics of debris flow. *J.Hydraulics Div.*, ASCE, 1978, 104(8):1153-1169.

Takahashi T. Debris flow mechanics, prediction and countermeasures. *Taylor&Francis/Balkema*, 2007.

Takahashi T. A review of Japanese debris flow research. *International journal of erosion control engineering*, 2009, 2(1):1-14.

Tang C., Rengers N., Van Asch Th.W. J., etc. Triggering conditions and depositional characteristics of a disastrous debris flow event in Zhouqu city, Gansu Province, northwestern China. *Natural hazards and earth system sciences*, 2011, 11:2903-2912.

Vandine F., Bovis M. History and goals of Canadian debris flow research, a review. *Natural Hazards*, 2002, 26: 69-82.

Wang Y.Y., Tan R.Z., Jan C.D., etc. Gravel accumulation in deposits of viscous debris flows with hyper-concentration. *Journal of mountain science*, 2009, 6: 88-95.

Whipple K.X., Dunne T. The influence of debris-flow rheology on fan morphology, Owens Valley, California. *Geological society of America bulletin*, 1992, 104:887-900.

Yano K., Daido A. Fundamental study on mud-flow. *Bulletin of the Disaster Prevention Research Institute*, 1965, 14(2), 69-83.