A debris flow phenomenological analysis in the vicinity of coastal regions

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Abstract

Debris flows are among the most frequent and destroying geomorphic processes. In order to reduce the risk, the present work places before the problem of how to intervene an analysis of the phenomenology and a study of the mechanisms of its triggering. After presenting and comparing in a critical way the main approaches to the problem, original thematic considerations are performed so to develop, in future investigations, a method applicable to study the dynamics of transport processes in debris flows.

1 Introduction

The problems concerning debris flows, for the augmented frequency of their happening and for their consequent affection to the anthropic system, have encountered an increasing interest both from the research groups and from the operators charged with land management and planning. A debris flow consists of a mass movement affecting sediments poorly sorted, shaken and mixed with water, which, being present as deposits in the mountain part of the basins, start to move due to alluvial events, determining sediment floods rapidly propagating downstream. As debris flows are among the most frequent and destroying geomorphic events, it exists the exigency to set up some criteria identifying risk areas and defining protection strategies. An approach concerning the mitigation of these phenomena is aimed at intervening on the natural system, trying to reduce the interactive potential through structural measures [1]. A direct intervention must anyway be flanked by an action on the anthropic system, mobilising people and resources, either temporarily with alert or evacuation systems or permanently with the regulation of the risk areas [2]. In a perspective of debris flow risk mitigation
and of development of realistic predictive models, it appears necessary, in this work, to place before the problem of the methods of intervention a complete analysis of the phenomenology, propaedeutical even to the study of the phenomenon at the first stages of motion. The main approaches \[3, 4\] to study the triggering of motion analyse the conditions which drive to instability in a detrital deposit initially static and so to dispersion of the particles inside the flow. The present work starts with a phenomenological analysis that, beginning with the general item of hyperconcentrated flows, is then particularised to the case of debris flows. A few aspects of interest in the hydrological study of debris flows are then highlighted and they prove to be helpful in setting up effective systems of prevention and prevision in the risk areas. Concerning the study of how debris flows trigger, different schemes of involvement and of solid staff transport inside a flow in a natural river bed are successively considered and critically compared. Finally the main conclusions obtained are analysed so getting information about possible future developments of the research.

2 Interaction between coastal dynamics and mass movements

The instability of detrital deposits apparently static is a common problem to many coastal zones where, due to processes of incision and erosion, superficial slips can easily happen. It exists so the exigency to set up methods analysing the conditions of instability so being able to determine the parts of a coastal region more subjected to risk, to predict the triggering conditions and the dynamics of the processes and to assess the possible interactions with the infrastructure and the anthropic system. The object of this research is to study not just those processes happening in correspondence to the coast but all the gravity induced ones, that are mass movements in closely related to sediments transport phenomena which happen both in underwater environment, far from the coast on the sea depth, and in subaerial one, in the basins located in the mountain sides close to mountainous coastal zones; both kinds, in fact, can have significant consequences on the equilibrium of the whole coastal system. On the one hand the vicinity of the coast is dominated by superficial erosion gravity-induced processes like slides and slumps. The latter ones consist of a quick downward rotation of detrital material and happen frequently after a rough variation of slope of apparently static detrital deposits or after coast erosion determined by sea waves (Figure 1). On the other, debris flows represent, among mass movements which can develop in an underwater or subaerial environment close to coastal ways, gravity-induced processes producing particularly significant morphologic changes on them. Debris flows can also represent the natural evolution of a slide or of a slump when particular conditions of fluidisation happen. Moreover, it is often believed that debris flows are just terrestrial phenomena, while they often actually happen also in marine environment. Common causes of submarine debris flows are the sharpening of the slopes on the sea-bottoms for the unceasing transport and mixing of sediments and the fluidisation induced by the earthquakes. Even if hidden to human eyes, submarine debris flows are not less dangerous of terrestrial ones: in fact they represent a
threaten for submarine ducts and cables and for off-shore structures; moreover, due to the superficial waves generation caused by them, they can potentially trigger a tsunami.

With respect to terrestrial debris flows, those submarine present a finer granular composition, they can develop in much less inclined slopes and, happening in underwater condition, the effect of gravity is significantly reduced due to buoyancy effects. This premised, the present study proposes an analysis of the phenomenology of debris flows trying to highlight the main characteristics of the process, which could describe every debris flow phenomenon, underwater or terrestrial.

3 Phenomenology

A hyperconcentrated flow is a moving fluid in which, anyway, the percentage in volume of solid material carried with respect to the total volume is elevate. Solid particles carried by a hyperconcentrated flow, according to origins of the forces, can be classified as bed load, suspended load and neutrally buoyant load [5]. The most qualifying aspects of debris flows are the reciprocal interaction between solid and liquid components and the inertial effects due to intergranular collisions and to the mixture deformation; these prerogatives allow a distinction from correlated phenomena in which just one component is dominant (streamflows, landslides and landslips). A typical debris flow wave, photographed at a certain moment of its propagation, can be spatially divided in three principal regions (Figure 2). The fore part of the flow (snout) is its front, and it presents an onward bulge mainly made of rocky fragments due to the phenomenon called "front effect", which can be described by the following dynamics [6]: local increment of the solid coarse fraction and local reduction of the liquid fraction, local reduction of the total flow rate and local velocity so determining a light slowing down of the arriving flow and in some cases a real stop. The second region (body) is characterised by an ever more tapered flow of water, fine fraction and sediments carried during the flow,
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while the last zone, thin and much more diluted presents an elevate mud concentration and it continues to flow even after the wave has passed.

Figure 2: different regions inside a debris flow wave.

The solid fraction can be subdivided in three classes: micrometric (μ), mesometric (mm) and macrometric (m); these classes are in tight correlation respectively to viscous debris flows, muddy and stony ones [7]. Typical velocities of the phenomenon have been observed between 0.5 and 20 m/s, which is a pretty wide range of variation due to the flow composition (concentration and dimension of the sediments) and to the geometry of the channel (slope, dimensions, tortuosity). Moreover generally a debris flow happens along particularly steep slopes; nevertheless the particular fluidity of this phenomenon makes it possible even on much less inclined surfaces: typical slopes observed vary between 15% and 32% [4]. Properties of debris flows mainly depend on the interactions between solid and liquid component. The presence of a fine fraction inside the interstitial fluid does not just influence its density, for which also V_{fine}, volumetric fraction occupied by fine fraction, that is silt and clay, will have to be considered, but also the effective fluid viscosity. Few characteristics, observed in debris flows and hereafter presented, are important in the dynamics of this phenomenon and because of that they should be conveniently considered in any modelling attempt. Dilatancy: in a granular system it is verified an increase in volume, in correspondence to rapid shearing, due to intergranular collisions and to the consequent dispersive pressure [8], determining an expansion of the interstitial space. Internal friction: debris flows show a behaviour which is intermediate between solids and liquids, result of friction and of the possible granular cohesion, and representable with Mohr-Coulomb’s yield criterion: $|\tau| = c + \sigma \tan \phi$, in which $\tau$ is tangential stress, $\sigma$ is normal stress, $c$ is cohesion and $\phi$ the friction angle. Fluidisation: given an initially static bed of solid particles crossed by a water flow, the solid phase progressively develops a nearly-fluid behaviour, further to the reduction of internal friction and to the bed expansion. Inverse grading: considering enough long time intervals of observation, the deposit of coarser clasts in correspondence to the free surface makes here the material to move more rapidly of that in the underlying layers, moving onward towards the fore part of the flow. The front so moves in a “rotating” way, sometimes compared to the motion of a conveyor belt (figure 3).
An explanation of this peculiarity is based on the kinematic sieving [9], consequence of the chaotic fluctuations of the particles; another explanation is possible by means of the dispersive model [10], characterised by larger strain rate, larger dispersive pressure and so more intense collisions in the lower layers.

Figure 3: effect of inverse grading on the movement of the front.

Energetics of a debris flow: studying energetics of a debris flow it has been successfully employed a physical analogy between the granular random motion inside the mixture and the thermal motion of molecules in the kinetic theory of gases: particles would fluctuate in the interstitial fluid like atoms in an ideal gas. The mean-square value of the random velocities of particles was first defined by Ogawa [11] as “granular temperature”, 

$$T = \left( \mathbf{u}_p - \bar{\mathbf{u}}_p \right)^2$$

where \( \mathbf{u}_p \) is the instantaneous grain velocities, \( \bar{\mathbf{u}}_p \) is the mean velocity of particles after a certain location and their difference represents the instantaneous deviation from the mean motion; \( T \) is twice the energy per unit mass contained in the random motions of particles. Generation of granular temperature inside a granular system is principally due to two mechanisms: collisional temperature transport, due to interaction of particles and streaming temperature transport due to their fluctuation [9].

4 Triggering of debris flows

To trigger a debris flow it is necessary that some force modifies the equilibrium condition of a static detrital deposit, so determining instability at least in correspondence to the more superficial portion and dispersion of particles inside the flow. The chances available are essentially two [4]: progressive increment of the
solid concentration in the superficial flow and soil liquefaction. In the first case it is necessary an external water supplying (meteorological events, landslides fluidisation, collapse of a natural dam). In the second mechanism instead, the detrital deposit already contains the requested amount of water to make it flow and it is the rapid tendency of shrinkage, typical of some loose soils, that, in conditions of partially limited drainage, determines the sudden growth of interstitial pressures and the consequent cancellation of the effective stresses (phenomenon of liquefaction), favouring the passage to a fluid and moving state. The study of the triggering conditions of a debris flow requires an analysis of the role played by the different forces acting in the generation of the motion. In Shields’ scheme [3], individual particle motion, it is evaluated the stability of a single particle related to the active drag forces due to the flow and to the resistive ones, due to the immersed weight, and eventually to the consequent at-the-bottom friction, in condition of imminent motion (figure 4). In conditions of static equilibrium the normal and tangential vincular reactions, respectively, are:

\[ R = \left[ \frac{(P - B) \cos \theta - F_L}{\rho_s - \rho_l} \right] \]

\[ A = \left[ (P - B) \sin \theta + F_D \right], \]

in which one has:

\[ P - B = (\rho_l - \rho_s) g \alpha_2 d^3 \]

unburdened weight, (B is buoyancy and P is weight),

\[ F_D = 0.5 C_D \rho_s \alpha_1 d^2 u^2 \]

drag force, weighed (B is buoyancy and P is weight),

\[ F_L = 0.5 C_L \rho_l \alpha_4 d^2 u^2 \]

lift force and \( \theta \) slope. Moreover \( u \) is the local velocity of the flow, \( \rho_l \) is the flow density, \( \rho_s \) is the density of the particle, \( C_D \) and \( C_L \) are drag and lift coefficients, \( \alpha_i \) are constants characteristic of the granulometry, \( g \) is gravity. Introducing \( u/u^* = \alpha_3 \), characteristic constant of the velocity profile, with \( u^* \) indicative velocity of the at-the-bottom stresses (\( \tau = \rho_l u^{*2} \)), the condition of imminent motion is reached for:

\[ A = R \tan \phi, \]

so obtaining:

\[ \phi_c = \frac{u^{*2}}{gd (\rho_s - \rho_l)/\rho_s} = 2 \frac{\alpha_2 (\cos \theta \tan \phi - \sin \theta)}{\alpha_1 \alpha_3^2 (C_D - C_L \tan \phi)} \]

(1)

The first member contains the dimensionless ratio between drag and stabilising forces called “index Shields’ number”. To assess the stability of the particles it is due to be compared the value of \( \phi \) with Shields’number: for \( \phi < \phi_c \) the particle is
stable, while for $\phi > \phi_c$ the particle is moving. Takahashi's model [4], massive movimentation, assumes a uniform layer of granular material with a thickness equal to $D$ and slope equal to $\theta$; it is hypothesised that at the moment when the water flow $h_0$ begins its motion, the porous gaps between particles is at an elevate saturation degree and a hydrostatic distribution of pressure is present in the interstitial fluid. Moreover, it is considered $a$ as the depth co-ordinate, with origin on the granular surface and positive sense towards the bottom of the river bed; besides, $a_L$ represents the point at which resistant stress and active stress become equal. In the direction parallel to the surface the active stress, due to both the weight of the superficial water and the weight of the layer “saturated” of sediments, is equal to: $\tau = \rho_i(h_0 + a) + a(\rho_s - \rho_i)\gamma g \sin \phi$. The resistant stress, instead, is assessed by means of Mohr-Coulomb's criterion: $\tau_L = c + C_v^* (\rho_s - \rho_i) k a \cos \varphi \tan \phi$, where $C_v^*$ is the maximum volumetric concentration of the sediments and $c$ is cohesion. Assuming a linear distribution for the tangential stress, two limit cases of triggering can happen. In the first one, $d\tau/da \geq d\tau_L/da$, the triggering condition results to be:

$$\tan \vartheta \geq \frac{C_v^* (\rho_s - \rho_i)}{\rho_i \left( \frac{h_0}{a_L} + 1 \right) + (\rho_s - \rho_i) C_v^* \tan \phi}$$

and many kinds of debris flows can be verified in relation to the position of the point $a_L$ intersection between the straight line $\tau_L$ and the straight line $\tau$ (figures 5 and 6). Just if $a_L \geq D$, which means $\tau \leq \tau_L$, no debris flow will be verified because of the bed stability. In the second case, $d\tau/da < d\tau_L/da$, it could be anyway verified a debris flow in the upper portion of the deposit ($\tau \leq a_L$) if $\tau \geq \tau_L$. But if $a_L$ is less than the diameter of the sediments just the superficial particles will be carried by the flow, and an individual particle transport (bed load and suspended load) will happen. Besides, if $a_L$ is much less than the height of the superficial flow $h_0$, the particles do not
have the chance to scatter in the whole depth of the flow, so determining an “immature debris flow”. So, in the second case, the triggering condition is:

\[
\tan \phi \leq \tan \theta < \frac{C^*_v (\rho_2 - \rho_1)}{\rho_1 + (\rho_s - \rho_1) C^*_v} \tan \phi
\]  

In a recent study [12] it has been introduced also the effect due to a single particle positioning with respect to the mean surface, through its exposure degree \( e \), which varies between 0 and 1 when the particle is completely hidden or exposed, respectively. Armanini & Gregoretti [12] modify then the balances in the condition of imminent motion, assuming \( \Delta = \rho_1/(\rho_s - \rho_1) \) and opportune functions of the exposure degree, \( f_i(e), f_2(e) \) and \( f_3(e) \), so obtaining an extension of eqn (1):

\[
\frac{u^{*2}}{gdA} = \frac{\alpha_2}{\alpha_1 f_1 \alpha_3^2} \left[ \frac{\cos \theta \tan \phi - \sin \theta - (1 - f_2)(1 - \alpha_2) \sin \theta}{\Delta \alpha_2} \right] (C_D + C_L \tan \phi) + \alpha_1 f_3
\]  

5 Critical considerations on the dynamics of triggering

Shields’s scheme [3] cannot be considered as exhaustive in the study of triggering of flows classifiable as debris flows, but it has to be integrated with Takahashi’s model [4] which considers the equilibrium of the whole layer at the bottom of the river bed. The study of how the motion triggers, by means of both the previously quoted approaches, is negatively affected by the presence of a few empiricism, as the relations there obtained are not directly comparable, as it will be shown afterwards. This could be due to the necessary schematisation, inevitable in any attempt of modelling, of the actions acting on the whole “granular mattress” at the bottom of the river bed. Remembering equation (1) of Shields’ approach, an analogous expression originating from Takahashi’s model must be investigated. If we set an equality between active and resistant stress in correspondence to \( a = a_L \) for \( c = 0 \), it can be obtained:

\[
\frac{\tau_0 / \rho}{g a_L (\rho_s - \rho_1)/\rho_1} = C^*_v \cos \theta \tan \phi - \left( C^*_v + \frac{\rho_1}{\rho_s - \rho_1} \right) \sin \theta
\]  

being \( \rho_1 gh_0 \sin \theta = \tau_0 \) the stress at the bottom of the river bed. Introducing, then, the friction velocity \( u^{*2} = \tau_0 / \rho_1 \) and setting \( a_L = nd \) with \( n \geq 1 \) as suggested in [4], it is possible to write an expression of the same kind of eqn (1):

\[
\frac{u^{*2}}{gd(\rho_s - \rho_1)/\rho_1} = n \left[ C^*_v \cos \theta \tan \phi - \left( C^*_v + \frac{\rho_1}{\rho_s - \rho_1} \right) \sin \theta \right]
\]  

Neglecting the constants of multiplication, it can be observed that the two relations have common solutions just if \( C^*_v = 1 \) and \( C^*_v = -\rho_1/(\rho_s - \rho_1) \) at the
same time. This missed superimposition suggests that other factors, as for instance the effect, not considered, of the superficial water infiltration inside the bottom of the river bed not completely saturated, could have not been accurately incorporated in the previous approaches and so, in order to perform a fully satisfactory extension of the models, further investigation is definitely considered as necessary. The study of the kinds of stresses acting on a granular deposit initially still, independently from the kind of approach considered, "individual particle movement" or "massive movimentation", clearly shows the importance of the river bed slope, which determines a significant variation of the active and resistant forces. While in correspondence to weak slopes the particles move essentially due to hydrodynamic forces, with a drag and lift action, when instead the slope is increasing the tangential component of the weight plays a not negligible role determining movimentations typical of debris flows in which the whole layer at the river bed bottom is involved. It has finally to be, anyway, observed that along the depth profile of the flow it is possible that different kinds of transport happen, due to the variation of the characteristics of the sediment and of the behaviour of the flow.

6 Conclusions

The increased frequency of happening of debris flows and their consequent interference with the anthropic system strongly highlight the exigency of setting up mitigation criteria with respect to debris flows risk by developing realistic and predictive physical models. Starting from the phenomenological investigation, that has allowed for putting in evidence the main dynamic characteristics of the phenomenon so enabling us to show strong and weak characteristics of the approaches nowadays available, original and critical considerations were here provided in order to develop, in future investigations, a modelling methodology applicable to the analysis of the dynamics of the transport processes and capable of a careful representation of the phenomenology.

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References


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