Hydrology

Investigation of the Dynamic Characteristics of Hyperconcentrated Alluvial Flows

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ABSTRACT. The general aspects of hyperconcentrated alluvial flows are given. Some problems connected with their dynamics at free-flow and pressure motion regimes are considered. The model of uniform motion of such flows is accepted as some working abstraction, serving as an instrument for further description of real processes taking place in nature.

The paper may interest specialists dealing with problems of scientific research in the fields of hydrology, hydraulics, chemical technology, food industry etc., when transporting materials along channels with different forms of cross-sections. *© 2010 Bull. Georg. Natl. Acad. Sci.*

Key words: *hyperconcentrated alluvial flow, flow core, flow discharge, average flow velocity.*

1. Introduction

Powerful flows, saturated with sediments including debris flows, are mainly formed in erosional downcuttings representing a whole system of beds in headwaters of mountain streams which, due to continuous hard rock destruction and their removal from the overlying areas, are filled with clastic mass later undergoing alternation, fragmentation and shredding under the influence of various natural factors. Mass weight formed as a result of the above-mentioned phenomena envelops detrital materials and fills the voids between them. Prepared in such a way in erosional downcutting debris mixture is in cohesive state, thus waiting for any reason, such as downpour, intensive snowbreak, groundwaters, etc, to collapse downstream, seizing on the way rock fragments, stones, trunks and so on. It turns then into a powerful debris flow with great destructive force [1-4]. Tills and subglacial deposits often represent already prepared debris mixture.

In case if these sediments are soaked with water by 10-20% (in mass) debris flow can be formed at large gradients [3]. If there are no glaciers the collapse of subglacial outcrops also causes its motion. Debris flows in this case may appear without downpours.

Debris flows can be formed on bare surfaces of steep slopes in headwaters of mountain streams caused by rainfalls after prolonged drought. As a result, the surface is covered with a waterproof layer of dust and in case of heavy rain almost a hundred per cent of runoff of storm rainfalls appears in the form of mud weight involving large quantity of rock fragments in its motion. The formed mixture moves down the bed of water flow in the form of hyperconcentrated (structural) debris flow (if the quantity of rainfall makes up 10-20% of weight of the whole debris mixture) or turbulent (low-concentrated) flow (the rainfall quantity amounts to 70-80% of the weight of the whole mixture) or rainfall flashflood (when the rainfall makes up more than 95% of the mixture weight) [1]. The density of hyperconcentrated mixture is

1.8-2.3 t/m^3; moving medium represents a plastic mudstone conglomerate.

Turbulent (low concentrated) debris flow presents water medium, often rich in colloid suspension. It transports crushed stone mass and singular large stones; its density varies from 1.1 to 1.7/t m^3, hard inclusions 10-70% in mass. Transporting medium is water or watercolloid mixture [1].

Debris flows according to density can be referred both to Newtonian and non-Newtonian liquids. That is why to solve some practical problems it is necessary to use the laws of mechanics of Newtonian and non-Newtonian liquids.

It should be noted that in water flows in which hyperconcentrated (structural) debris flows are formed, the formation of low-concentrated debris flows is possible, while with the formation of turbulent debris flows it is not necessary for structural debris flows to be formed in the same basin.

Below we shall consider hyperconcentrated debris flows as the most dangerous and destructive phenomena with uniform regime of motion. They are formed considerably seldom but the damage they bring is so great that they deserve special attention.

The authors realize that the model of uniform regime of motion of hyperconcentrated debris flow is an abstract and, in real conditions it mainly moves in the wave regime [1, 2], but the solution of many complex dynamical problems of this phenomenon is not possible without approximation of such fictitious approach.

We present the simplest approach for statement of the real process of dynamics of debris flows from the point of "quasiuniform" position. This is the simplest and convenient for analysis method of investigation, where simplicity is effected by means of averaging by the along free cross-sectional area of the flow physical values of the composite phases and initial equations at the stage of their composition, where flow mixture is considered as quasicontinuum, giving the possibility to describe the polyphase flows with single-phase medium equations.

Such assumption at analysis allows us to operate with the average parameters and characteristics of the mixture (specific weight, density, viscosity, etc.). The above-said apparent characteristics are average-weighted and do not correspond to the properties of the components of the mixture (water, stone, fine-grained fraction, colloid particles, etc).

If we treat the phenomenon from the position of one-dimensional (hydraulic) problem, then the real process is more simplified from the practical point of view (especially for bed processes) and in most of the cases the finally obtained dependences give satisfactory results. At that together with physical average characteristics one should operate with average hydraulic elements of the flow area passage (average speed of the mixture, along the free cross-sectional area discharge, total resistance to the motion, etc.) [2].

The simplicity of the approach from the one-dimensional point of view is profitable in the way that interaction between phases and bed can be estimated by integral resistance member, which is easily subjected to measurement both in the laboratory and field conditions [5,6].

2. Free-pressure "abstract uniform" motion of hyperconcentrated debris flow in watercourse bed.

Let us assume that hyperconcentrated debris flow moves in watercourse bed with free pressure flow in "abstract uniform" regime, general depth H (Fig. 1).

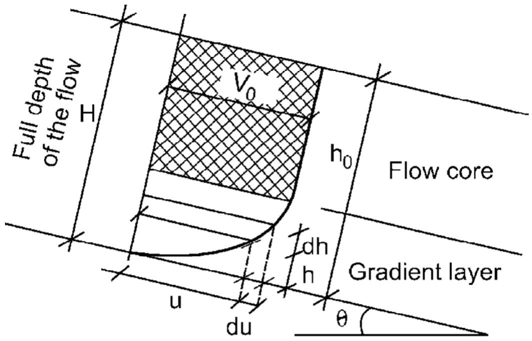

Fig. 1. Diagram of velocity distribution in hyperconcentrated plane debris flow at pressure uniform motion: longitudinal section.

Then the equation of Shvedov-Bingham for non-Newtonian liquids will be [1-3, 8, 10, 11].

$$\tau = \tau_0 + \mu \frac{du}{dh}. \quad (1)$$

here

τ – tangent direction along the depth of the flow;

μ_0 – primary resistance to the shift of debris mixture;

μ – coefficient of dynamic viscosity;

u – local velocity along the depth in gradient layer;

h – flowing coordinate of gradient layer.

Taking into consideration that $\mu = \nu\gamma / g,\ \gamma = \rho g$ and $\tau_0 = \gamma i h_0$, where

ν – coefficient of kinematic viscosity;

γ – specific weight of debris mixture;

g – acceleration of gravity;

ρ – density of debris flow;

i – gradient of the bed's bottom $i=\sin\theta$;

θ – angle of gradient of the bed's bottom to the horizon.

h_0 – core depth (without gradient layer) flow;

Taking into account the above designations the formula (1) will take the form:

$$du = \frac{gi}{\nu}(H - h - h_0)dh . \quad (2)$$

After integrating (2) with account of the boundary conditions, when h=0, u=0 and changes from h=0 to $h = (H - h_0)$ we can get the law of velocity distribution in gradient layer depth:

$$u = \frac{gi}{\nu}\left[Hh - \frac{h^2}{2} - h_0 h \right]. \quad (3)$$

Dependence (3) allows to construct the velocity distribution diagram by the vertical in gradient layer, i.e. in the limits of h=0 to $h = H - h_0$.

Let us define now the average velocity V_1.

Integrate (2) in the limits of h=0 to $h = (H - h_0)$ and divide by $(H - h_0)$, we receive

$$V_1 = \frac{gi(H - h_0)^2}{3\nu}. \quad (4)$$

In the case when h=0 from (3) we get u=0, and when $h = H - h_0$ instead of dependence (3) we shall have:

$$V_0 = \frac{gi}{2\nu}(H - h_0)^2 . \quad (5)$$

$V_0 = V_{\max}$ is the core velocity (i.e. gradientless layer) of the flow. When h_0=0, $V_0 = \frac{giH^2}{2\nu}$ [6].

In order to get average cross-section velocity, we define debri's discharge in gradient layer per unit of the flow width

$$q_1 = V_1(H - h_0) . \quad (6)$$

Taking into account (4) instead of (6), we obtain:

$$q_1 = \frac{gi}{3\nu}(H - h_0)^3 . \quad (7)$$

Define discharge per width unit in the core of flow accounting (5)

$$q_0 = V_0 \cdot h_0 = \frac{gih_0}{2\nu}(H - h_0)^2 . \quad (8)$$

Full flow discharge per width taking into account dependences (7) and (8) will be:

$$q = q_1 + q_0 = \frac{gi}{\nu}(H - h_0)^2 \left(\frac{2H - h_0}{6} \right). \quad (9)$$

Average velocity of the total flow per width unit will be:

$$V = \frac{q}{H} = \frac{gi(H - h_0)^2}{6\nu H}(H - h_0) \quad (10)$$

In that case when h_0=0 and H>0, then

$$V = \frac{2}{3}V_0 = \frac{2}{3}V_{\max} \quad (11)$$

and obtain well-known dependence of hydraulics [6].

Divide (5) by (10). After some transformations we receive:

$$\frac{V_0}{V} = \frac{3H}{2H - h_0}$$

from which we have

$$h_0 = H\left(2 - 3\frac{V}{V_0} \right). \quad (12)$$

Dependence (12) gives the possibility to determine the core depth of the flow (when $2 > 3\frac{V}{V_0} > 1$) as according to the nature data and laboratory experiments V, V_0 and H are easy to measure values among which V_0 is practically surface flow velocity.

Knowing h_0 and other hydraulic parameters of the flow depth, gradient of the bed and average velocity we can define the viscosity of the medium, also $\tau_0 = \gamma i h_0$ and judge about the break up moment of the ready mixture from erosion cutting and predict the place of the flow halt on the cone debris [9].

At high flow velocities in gradient layer turbulent regime of motion is sometimes noted.

If we use the dependence for determination of pressure loss in the form [2]

$$h_\ell = i\ell \tag{13}$$

where ℓ is the length of part of the bed, then from dependence (4) it follows

$$i = \frac{3V_1\nu}{g(H-h_0)^2}. \tag{14}$$

If we insert into (13) correlation (14) we get:

$$h_\ell = \frac{3\nu}{g(H-h_0)}\frac{\ell}{(H-h_0)}V_1 \cdot \frac{2V_1}{2V_1} \tag{15}$$

and designating

$$\mathrm{Re}_1 = \frac{V_1(H-h_0)}{\nu} \tag{16}$$

instead of (15) we shall have

$$h_\ell = \frac{6}{\mathrm{Re}_1}\frac{\ell}{(H-h_0)}\cdot\frac{V_1^2}{2g}, \tag{17}$$

where Re_1 – Reynolds Number for gradient layer of the debris flow.

Taking into account that at turbulent regime of motion

$$V = \sqrt{\frac{8g}{\lambda}}\sqrt{Ri}, \tag{18}$$

where $C = \sqrt{\frac{8g}{\lambda}}$ Chézy coefficient [6] from where

$$\lambda = \frac{C}{8g} \tag{19}$$

λ – D'Arcy coefficient, then instead of (17) we can write:

$$h_\ell = \frac{C^2}{8g}\cdot\frac{\ell}{(H-h_0)}\cdot\frac{V_1^2}{2g}. \tag{20}$$

Assuming $V_1 = V$ and comparing (15) or (17) with (20) we shall have:

$$\frac{C^2}{8g} = \frac{6\nu H}{V_1(H-h_0)^2}$$

or

$$C = \sqrt{48g\,\mathrm{Re}_1} \tag{21}$$

i.e.

$$C = 21.7\sqrt{\mathrm{Re}_1}. \tag{22}$$

For water flow we have [5]

$$C = 1.81\sqrt{\mathrm{Re}_1}. \tag{23}$$

If we compare (22) with (23) we shall have $\frac{C}{C_0} = \frac{21.7}{1.81} = 12$, and this is quite logical accounting hyperconcentration of debris flow.

3. Pressure "abstract uniform" motion of hyperconcentration debris flow in cylindrical constructions.

The topography of the territory often requires passage of hyperconcentrated debris flow in cylindrical structures, in which, in some cases, pressure regime of motion is observed (structures under car roads and railways, tunnels for debris flows, removal into other beds etc.).

We extract in the flow the cylindrical compartment of the debris flow with radius *r*, the lateral surface of which lags behind from the axis of cylindrical structure with radius *R* (Fig. 2).

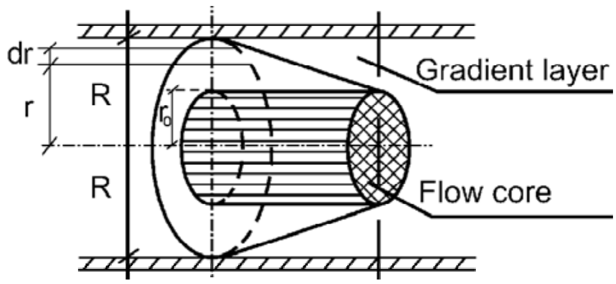

Fig. 2. Diagram of velocity distribution in hyperconcentrated debris flow at pressure motion in the structure with cylindrical cross-section form: longitudinal cross-section.

Then for cylinder we can write [6]:

$$\tau = \rho g \frac{r}{2} J. \tag{24}$$

where τ is tangential stress on the lateral surface released in debris flow on the cylinder with radius of cross-section *r*. With the increase of *r* (from the axis to the wall of the cylinder) local velocity in gradient layer changes and it decreases; that is why velocity gradient $\frac{du}{dr} < 0$. While tangential stress τ is positive in the Shvedov-Bingham formula (1) the sign minus is introduced and has the form:

$$\tau = \tau_0 - \mu \frac{du}{dr}. \quad (25)$$

Taking into account that $\tau_0 = \rho g \frac{r_0}{2} J$, where r_0 is a radius of flow core, with account of designations (25) it takes the form:

$$\gamma \frac{r}{2} J = \gamma \frac{r_0}{2} J - \mu \frac{du}{dr}, \quad (26)$$

where J is the hydraulic gradient.

From (25) after integration it follows

$$u = \frac{r_0 Jg}{2\nu} r - \frac{Jg}{2\nu} \frac{r^2}{2} + C, \quad (27)$$

here C is integrated constant.

When $u = 0$, $r = R$, then

$$C = \frac{Jg}{4\nu} R^2 - \frac{r_0 Jg}{2\nu} R. \quad (28)$$

Inserting (28) into (27) after simple transformations we receive:

$$u = \frac{Jg}{4\nu}\left(R^2 - r^2\right) + \frac{r_0 Jg}{2\nu}(r - R). \quad (29)$$

Dependence (29) allows to construct a diagram of the velocities in gradient layer of the flow. When $r=R$, instead of (29) we get $u=0$ that corresponds to reality (i.e. on the contact surface of the debris with directing walls of the structure the velocity is equal to 0).

Determine the core velocity of hyperconcetrated debris flow. Assume $r=r_0$, then core velocity V_0 is estimated respectively

$$V_0 = \frac{Jg}{4\nu}\left(R - r_0\right)^2. \quad (30)$$

Dependence (30) allows to define the core flow motion velocity in cylindrical structures.

Core flow discharge with account of (30) will be:

$$Q_0 = V_0 \pi \cdot r_0^2 = \frac{\pi \cdot r_0^2 Jg\left(R - r_0\right)^2}{4\nu}. \quad (31)$$

We define average flow velocity in gradient layer:

$$V_1 = \frac{1}{R - r_0} \int_0^{R - r_0} u dr. \quad (32)$$

Inserting (29) into (32) after simple transformations we get:

$$V_1 = \frac{Jg\left(R - r_0\right)^2}{6\nu}. \quad (33)$$

Flow discharge in gradient layer will be:

$$Q_1 = \pi \cdot \left(R - r_0\right)^2 V_1.$$

Then with account of (33) we receive:

$$Q_1 = \frac{\pi g J}{6\nu}\left(R - r_0\right)^4. \quad (34)$$

Total discharge of the debris flow will be:

$$Q = Q_1 + Q_0$$

or with account of (31) and (34) we get:

$$Q = \frac{\pi g J\left(R - r_0\right)^2}{2\nu}\left[\frac{r_0^2}{2} + \frac{\left(R - r_0\right)^2}{3}\right]. \quad (35)$$

The average cross section velocity of hyperconcentrated flow will be:

$$V = \frac{gJ\left(R - r_0\right)^2}{2\nu R^2}\left[\frac{r_0^2}{2} + \frac{\left(R - r_0\right)^2}{3}\right]. \quad (36)$$

4. "Abstract uniform" motion of hyperconcentrated debris flow in the gallery with rectangular cross-section (at B>>2H).

Using the equation (1) of Shvedov-Bingham as primary dependence

$$\tau = \tau_0 - \mu \frac{du}{dh}, \quad (37)$$

we take into account that $\tau_0 = \gamma h_0 J$; $\tau = \gamma J(h_0 + h)$, dependence (37) will have the form:

$$du = \frac{\tau_0}{\mu} dh - \frac{\tau}{\mu} dh. \quad (38)$$

Assume (Fig.3): B is the width of the construction (gallery), h_0 – half of the flow core depth; H – half of the height of the gallery.

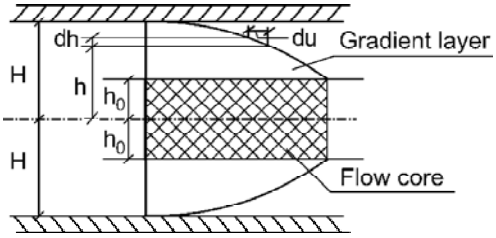

Fig. 3. Diagram of velocities distribution in hyperconcentrated debris flow at pressure motion in a structure with rectangular cross-section; longitudinal cross-section

From (38) we receive

$$du = \frac{h_0 gJ}{\nu} dh - \frac{(h+h_0)gJ}{\nu} dh. \quad (39)$$

Integrating (39) with account of boundary conditions gives:

$$u = \frac{gJ}{2\nu}\left[(H-h_0)^2 - h^2\right]. \quad (40)$$

Dependence (40) allows to construct a diagram of the distribution of the velocities in gradient layer in the gallery.

When h=0 we receive core flow velocity:

$$V_0 = V_{\max} = \frac{gJ}{\nu}(H-h_0)^2. \quad (41)$$

Let us define the core discharge per width unit:

$$q_0 = 2V_0 h_0 = \frac{gJh_0}{\nu}(H-h_0)^2. \quad (42)$$

Average velocity of the flow core:

$$V_0 = \frac{q_0}{2h_0} \frac{gJ(H-h_0)^2}{2\nu}. \quad (43)$$

Divide this expression by $(H-h_0)$ and estimate the debris flow discharge ingredient layer per width unit and taking into account (43), we receive:

$$q_1 = \int_0^{H-h_0} \frac{gJ}{2\nu}\left[(H-h_0)^2 - h^2\right] dh.$$

After integrating we have:

$$q_1 = \frac{gJ(H-h_0)^3}{3\nu}. \quad (44)$$

Average velocity in gradient layer will be:

$$V_1 = \frac{q_1}{(H-h_0)} = \frac{gJ(H-h_0)^2}{3\nu}. \quad (45)$$

Flow discharge per width unit:

$$q = q_0 + q_1 = \frac{gJh_0}{\nu}(H-h_0)^2 + \frac{gJ(H-h_0)^3}{3\nu}.$$

i.e.

$$q = \frac{gJ}{\nu}(H-h_0)^2\left[h_0 + \frac{(H-h_0)}{3}\right]. \quad (46)$$

Full flow discharge in the gallery

$$Q = 2qB = \frac{2BgJ}{\nu}(H-h_0)^2\left[h_0 + \frac{(H-h_0)^2}{3}\right]. \quad (47)$$

Thus the method of calculation of the main hydraulic indices of hyperconcentrated debris flows in the galleries is established.

The obtained results enable to compare them with the data of nature [4], allowing to evaluate the validity of some important and difficult parameters of hyperconcentrated debris flows, practically not amenable to experimental determination.

Conclusion:

1. Hyperconcentrated debris flow is considered to be a medium having rigid inner structure. The obtained dependences will serve as the basis for solution of some practical problems;

2. The proposed dependences differ from other techniques of estimation by their ability to solve parameters of debris flows not amenable to evaluation.

ჰიდროლოგია

მყარი მონატანით ჰიპერკონცენტრირებული ნაკადების დინამიკური მახასიათებლების გამოკვლევა

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** აკადემიკოსი, საქართველოს მეცნიერებათა ეროვნული აკადემია*
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მყარი მონატანით ჰიპერკონცენტრირებული ღვარცოფული ნაკადები ხასიათდებიან ხისტი შინაგანი სტრუქტურით. სიჩქარის გრადიენტს ადგილი აქვს მხოლოდ მიმმართველი კედლების ნაკადის ზედაპირთან შეხების მიმდებარე შრეებში.

შემოთავაზებულია მყარი მონატანით ჰიპერკონცენტრირებული ღვარცოფული ნაკადების ,,კვაზიერთგანზომილებიანი" მოძრაობის განტოლებები როგორც უდაწნეო ასევე დაწნევიანი ფორმით გადაადგილების შემთხვევებში.

მიღებული საანგარიშო დამოკიდებულებები მომავალში საფუძვლად დაედება ამ ტიპის ნაკადების დაუმყარებელი მოძრაობის საკითხების შესწავლას.

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