Determination of the mean velocity of mudflows (debris flows) taking into account their life cycle

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Abstract. The paper is about calculation of the mean velocity of the mudflows. A mudflow is unsteady, non-uniform two-phase flows with high concentration of solid particles. Basic characteristics (depth, width, particle mean concentration and diameter) of a mudflow change in wide range (in time and in space), thus should be considered as a dynamic system. Existing empirical formulas for the mean velocity not for its. However, the principle of calculating the mean velocity must change for each phase of the lifecycle. Comparison of the calculated formulas and search for the closest ones to the measured also discussed. We give recommendations for calculating mean velocity of mudflows at any time during its moving.

1. Introduction

Mudflows and debris flow occurs in mountain areas worldwide. Debris flow (or mudflows, mudslides) destroy private and industrial structures in various parts of the world, Europe and Russia. If the territory is poorly populated (or there is no industry), it does not need engineering protection. But there are a large number areas (regions), were debris flow can destroy lands, territory, recreation, ski base, industrial zones, objects of engineering infrastructure (roads, bridges, tunnels, power lines, gas pipelines, oil pipelines, etc.) hydro-power structures in the beds of mudslides, as well as directly to the homes of the local population.

The main parameters of the mudflow flow must be known in order to design and effectively operate anti-settlement structures. The parameters vary over a very wide range (see table 1). Despite the fact that the most common flows have rate < 10 m3/sec it is very important to take into account the entire range of possible values. Slope limitation < 20 shows that two phases flow can move in the range (0 – 20 per cent). While the lower limit of slope for flow formation is in this range.

Table 1. Basic kinematic characteristics of debris flow.

| Characteristics | Symbol | Dimension | Range      | Note                                                                 |
|-----------------|--------|-----------|------------|----------------------------------------------------------------------|
| Density         | \( \rho_m \) | kg/m³     | 1100 - 2600 | High concentration of solid particles (50-60%). The maximum value is in the head, the minimum value is in the tail of the mudflow |
| Flow rate       | \( Q_m \) | m³/s      | 500 - 2000  | The maximum flow rate of a mudflow can exceed the maximum flow rate of a water stream in the same riverbed by tens of |
2. Literature Reference

Flows with high concentrated solid particles have been classified by the National Research Council (NRC) (1982) as mudfloods, mudflows and debris flows [1]. Physical processes difference these types of flows and based on the rheology of the water-sediment mixture [2-5]. Julien and Leon [6] proposed classification for hyperconcentration sediment flows based on the dominant shear stresses, which present in table 2.

| Type of flows | Predominance of shear stresses |
|---------------|-------------------------------|
| Mudflows      | viscous stress                |
| Mudfloods     | turbulent stress              |
| Debris flow   | dispersive stress             |

Table 2. Classification of flows (point of view – dominant shear stresses).

The vertical distribution of solid particles, which is present in mudflows, causes the variability of viscosity (and hence tangential stresses) along the live section of the flows. For two-phases flows, it is proved that the viscosity increases from the solid boundaries to the main flow. The cross section velocity distribution is related to the distribution of shear stresses and reflects the mechanism for generating energy costs for movement. The hypothesis of Velikanov M.A. about the work of viscous forces in the cross section formed the basis of experimental research at the Department of hydraulics of the Moscow state technical University, which is conducted from the 1930s to the present time [7-12].

Classification of mudflows is necessary to determine the levels of their capacity of the transport. Capacity of the transport is the amount of solid particles with a given hydraulic size that rises up from a unit area [10, 11]. Table 3 shows the classification of flows in terms of particle characteristics.
Table 3. Classification of flows (point of view – characteristics of solid particles).

| Type of flow           | Characteristics of solid particles contained in the stream                      |
|------------------------|---------------------------------------------------------------------------------|
| Water-stone            | Large stones, boulders, rock fragments                                          |
| Water-sand, Water-dusty| Sand, dusty material                                                             |
| Mud                    | Clay, a small concentration of stone, \( \gamma = 1.5 \ldots 2.0 \) t/m\(^3\)    |
| Mudstones              | Clay (predominates), stone \( \gamma = 2.1 \ldots 2.5 \) t/m\(^3\)              |
| Stone and mud          | Clay, stone (predominates)                                                       |
| Water-snow-and-stone   | Soil, silt, ice                                                                  |

Starting from mud to water-snow-stone streams have high viscosity and plasticity. The presence of a sufficient amount of solid particles in the stream (more than 5%) of small fractions (dust, clay, etc.) creates the effect of a "heavy liquid", which facilitates the weighted transfer of large particles.

3. Methods

Mudflow from the point of view of two-phase flow mechanics is a complex, unsteady interaction of two phases (liquid – water and solid-rock fragments, soil, ice, etc.). Mudflows are characterized by non-stationary time, density, and geometric characteristics. The study of such flows is necessary to effectively extinguish energy and reduce the destructive effect of the mudflow movement.

Flow formation schematic diagram in figure 1 shows where solid particles start or finish to move (1 – area of born and 3 – area of deposit) and were high capacity to move (2 – area of transit). A mudflow is a stream characterized by a high concentration of solid particles. The flow concentration is the number of solid particles that pass through the live section of the flow per unit of time.

![Figure 1. Scheme of debris flow.](image)

A mudflow is an unsteady two-phase flow, which parameters vary over a very wide range. Changes in the basic kinematic characteristics over time can be estimated using the mudflow life cycle shown in figure 2.
2 areas - Area of transit. Dynamic stage. Sharp increase in depth, channel width, velocity and consistency. $d_{av}$ reaches the maximum value. Evolution.

3 areas – Area of deposits. Stopping the mudflow. The formation of mud deposits. $Q_m$ decreases, the flow becomes single-phase. Transition.

4. Results

The mean cross section flow velocity is the main characteristic to calculate the pressure of a debris mass on the barrier. Methods for estimating the mudflow velocity are different:

1) Devices installed near a mudflow channel captures this tremor and this sound, which can even indirectly determine the size of the mudflow, its velocity and density.

2) The results of video recording of a mudslide, when determining the geometric characteristics of the mudflow bed, make it possible to estimate the velocity as a path divided by time.

3) Calculations using empirical formulas.

Table 4 was compiled to analyze various formulas for calculating the mudflow velocity [13-17].

| Formula | Author | Note |
|---------|--------|------|
| $V_m = 4.83H^{0.5}(\sin\alpha)^{0.25}$ | I.I. Herhuidze | Were $H$ – depth. Incoherent flows |
| $V_m = 4.5H^{0.67}I^{0.17}$ | V.V. Golubcov | $I$ - slope for coherent mudflows |
| $V_m = 3.75H^{0.5}I^{0.17}$ | | |
| $V_m = 8.05H^{0.58}I^{0.3}$ | Khan | |
| $V_m = \frac{6.5R^{2/3}I^{1/4}}{\sqrt{\rho_m\rho_s - \rho_s} + 1}$ | M.F. Sribny | $R$ – hydraulics radius ($= \omega / \chi$, $\omega$ - cross section area, $\rho_s$ - density of solid particles, $\rho_m$ - density of mudflows) |
| $V_m = 4.25R^{2/3}I^{1/4}$ | Formula Emercom Russia | Simplified formula (assumption of equality of solid and liquid volumes) |
| $V_m = 11.4H^{0.5}(\omega \sin\alpha)^{1/3}$ | Anna Paris | $\omega$ - hydraulic size of solid particles |
| $V_m = 5.75u^* \log \frac{H}{d_{50}}$ | Pierre Y. Julien and Anna Paris | $u^* = \sqrt{gR^f}$ – dynamic velocity, $d_{50}$ - median grain diameter |
Given in table 4 formulas are empirical and are regulated and good work in established limits which are obtained. In common mean velocity is complex function of number parameters:

\[ V_m = f (H, I, R, \rho_m, \sigma, \lambda, \ldots) \quad (1) \]

However, in practice it is not possible to take them all into account. So we use parameter viscosity \(( \mu_m \rangle \) of flow as aggregating parameter to takes into account all these factors. The experimental material, of which the calculations of the mean velocity were made, were obtained when analyzing of mud-stone mudflows [18-20]. The calculations are presented in table 5 and figure 3.

**Table 5. Results of calculations.**

| Segment | Mean velocity (actual), \( V_m \) m/s | \( \mu_m \) kg·s/m² | Mean velocity (calculated), m/s |
|---------|----------------------------------|------------------|--------------------------------|
|         |                                  | formula (3)     | formula (4)     | formula (5)     | formula (6)     | formula (7)     | formula (8)     |
| segment 1 | 8                                | 0.46             | 3.0             | 4.8             | 4.5             | 3.0             | 6.1             | 7.3             |
| segment 2 | 8                                | 4.04             | 5.2             | 9.0             | 9.4             | 6.2             | 10.5            | 17.9            |
| segment 3 | 6.5                              | 4.53             | 4.8             | 8.9             | 8.7             | 5.7             | 11.0            | 19.0            |
| segment 4 | 4                                | 1.70             | 3.7             | 5.9             | 5.9             | 3.9             | 7.1             | 9.7             |
| segment 5 | 3                                | 1.84             | 3.2             | 5.5             | 5.1             | 3.3             | 7.1             | 9.3             |
| segment 6 | 2                                | 0.98             | 2.5             | 4.0             | 3.7             | 2.4             | 5.3             | 5.7             |

**Figure 3. Results of calculation.**

Analysis of the obtained data shows a large spread of calculated velocity values, and none of the formulas shows satisfactory convergence with the results of field measurements at all stages of the mudflow life cycle. The formulas proposed by the Ministry of emergency situations and Pierre Y. Julien and Anna Paris showed the highest levels of mean flow velocity, as a result of which their use will lead to an overestimation of the predicted consequences of a mudflow.
5. Discussion
The existing formulas for calculating the mean mudflow velocity are a modification of the Shezi formula with some constants that cannot be such, since mudflows have different particle size distribution of the solid phase and its concentration in the flow. Comparison of the existing calculation formulas with field measurements shows that it is not sufficient to use the flow slope and depth as the only parameters for determining the mean mudflow velocity. A mudflow is a movement of a complex, unsteady two-phase flow, the parameters of which vary over a very wide range of time, and therefore it must be considered in parts, in accordance with the stages of its life cycle (determining the viscosity of the mudflow). Using the mudflow viscosity as an additional parameter that characterizes the ability to resist movement and transport of solid particles will allow you to divide the mudflow into segments and determine the mean velocity on each of them using the most optimal calculation formula.

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