ON THE MOTION OF STRUCTURAL MUDFLOWS

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Abstract

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GEOPHYSICS

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Sudden short-term floods arising in mountain regions as a result of intense downpours form mudflows (debris flows or "seli"). They differ from ordinary water flows in that they wash large quantities of fine earth from mountain slopes and also entrain into their motion the weathering products of hard rocks. A significant content of the solid phase changes the physical properties of the flow and its dynamic characteristics and gives the mudflow great destructive force. The harmful action of mudflows consists chiefly in the burying, silting, and destruction of populated places, railways and highways, bridges, etc. Mudflows often carry boulders weighing tens of tons.

If the basis of the solid phase of a mudflow consists of clayey and silty particles (colloidal and close to them) and the amount of water in the mudflow is relatively small, then the mudflow is a compact structure possessing elastic-viscous-plastic properties. Such flows we call structural or bound. Qualitatively, such a flow differs from a water flow and represents a medium intermediate between a liquid and a solid body. At rest, the mass of such a flow is a non-disintegrating structure. The structural state of the mudflow mass is due to the mutual molecular attraction of hydrophilic colloidal clay particles ([1],[2]).

Water in such a structure is present both in the form of hydrate shells and in an immobilized state, being trapped in the cells of the spatial structure. The colloidal particles forming this structure constitute the active part of the mudflow, allowing large heavy inclusions not to sink to the bottom under the action of gravity but to remain in the flow in a suspended state.

An experimental investigation* ([3]) showed that the ability of a structural mudflow to keep large heavy inclusions in suspension is a function of the effective (structural) viscosity η_e and the density γ_c of the mudflow mass forming the flow, while the viscosity, in turn, depends on the dispersity of the particles. The more clayey colloidal particles there are in the soil, the lower the concentration of the solid phase of the flow at which the given viscosity is attained. This proposition is illustrated by Table 1, which gives values of the dynamic structural viscosity of a mudflow mass, formed by soils of different fatness, determined by the Stokes falling-ball method: composition 1 is a fatter soil containing 45% clay particles, and composition 2 is a less fatty soil containing 18% clay particles. The range of concentrations of the solid phase in the liquid corresponds to fluctuations in the unit weights of natural mudflows.

* Conducted at the All-Union Scientific Research Institute of Transport Construction.

It is seen from Table 1 that, in order to obtain a viscosity of 3.7–3.8 poise, a concentration of silty loam in water K equal to 66% is required, whereas the concentration of fat clay is only 35%. Conversely, at one and the same concentration of 55% (at $\gamma_c = 1.5$ g/cm^3), the mudflow mass formed by loam had a viscosity of 1 poise, while the mass formed by clay had a viscosity of 400 poise.

Experiments to determine the supporting capacity of a mudflow mass, carried out by placing on its surface a successively increasing load (in the form of cement, tin, and lead balls of various sizes), showed that the magnitude of the load at which a heavy body does not sink to the bottom but remains suspended depends entirely on the viscosity of the mass and, at a given viscosity, does not depend on its concentration (bulk density).

Table 1

Composition 1 (fat)	Composition 1 (fat)	Composition 1 (fat)	Composition 2 (lean)	Composition 2 (lean)	Composition 2 (lean)
γ_c, g/cm^3	K, %	η_e, poise	γ_c, g/cm^3	K, %	η_e, poise
1.50	55	400	1.77	77	15.2
1.39	43	55	1.73	69	7.5
1.34	41	14.7	1.66	66	3.8
1.31	39	10.0	1.58	60	1.7
1.27	35	3.7	1.54	58	1.3
1.20	28	1.2	1.50	55	1.0

The critical value of the viscosity η_0, above which the mudflow mass possesses the ability to hold heavy inclusions within itself, according to experimental data is 2.5–3 poise (i.e., approximately 250–300 times greater than the viscosity of water). This value also characterizes the approximate boundary between cohesive and noncohesive flows.

The motion of a cohesive (structural) flow differs from the flow of an ordinary "Newtonian" liquid in that it begins only after the acting stress τ overcomes the initial resistance to shear τ_0. Then follows the stage of structural destruction, when the structural viscosity decreases as τ increases. In this phase the motion of a structural flow must be described by the hydrodynamic equation

$$\tau = \alpha\tau_0 + \eta^* \, dv/dn, \qquad (1)$$

Fig. 1. Diagram of hydrodynamic states of a structural flow from the beginning to the end of its motion

Figure 1: Fig. 1. Diagram of hydrodynamic states of a structural flow from the beginning to the end of its motion

where $0 \leq \alpha \leq 1$; $\alpha\tau_0$ is the part of τ_0 that successively decreases as τ increases; dv/dn is the velocity gradient; at $dv/dn = 0$, $\alpha = 1$; at $dv/dn = [dv/dn]_1$, $\alpha = 0$; η^* is the plastic viscosity of the flow with its structure destroyed to one degree or another. Formula (1) may be written as follows:

$$\tau = \alpha\tau_0 + \eta^* dv/dn = \eta_\mathrm{e}\, dv/dn,$$

whence

$$\eta_\mathrm{e} = \eta^* + \frac{\alpha\tau_0}{dv/dn}.$$

As dv/dn increases, $\alpha \to 0$ and η_e decreases, tending toward η^*. With further increase of the velocity gradient dv/dn, after the acting stress τ exceeds the magnitude of the critical stress τ_1, corresponding to complete destruction of the structure (i.e., at $[dv/dn]_1$) and elimination of the core, the third stage begins, which may be called the stage of viscous flow, since the structure of the flow is destroyed and, as in an ordinary liquid, the state of the flow may be described by Newton’ s equation:

$$\tau = \eta_\mathrm{e}\, dv/dn, \tag{2}$$

where, therefore, $\eta_\mathrm{e} = \eta^*$ when $dv/dn \geq [dv/dn]_1$ and $\alpha = 0$.

The motion of a flow with an incompletely destroyed structure should be described by the same equation in the case where there is steady motion corresponding to some definite degree of destruc-

of the structure, and no further destruction or strengthening of it occurs. The simple application of the Shvedov-Bingham equation

$$\tau = \tau_0 + \eta_\mathrm{e}\, dv/dn \tag{3}$$

to the description of the moving system is improper, since with an increase in shear stress the structural bonds between particles become increasingly weakened, and the simple addition of a static quantity, such as τ_0, to a dynamic velocity gradient does not correspond to the actual picture of motion. In reality, as the velocity of motion increases

Fig. 2. Curves of the dependence of the velocity of motion of a structural debris-flow mass v_{s} on the depth of flow h

Figure 2: Fig. 2. Curves of the dependence of the velocity of motion of a structural debris-flow mass v_{s} on the depth of flow h

Fig. 1. Diagram of the hydrodynamic states of a structural flow from the beginning to the end of its motion

and the structural bonds are destroyed, an ever smaller fraction of τ_0 takes part in resistance to motion, until finally, at $\alpha = 0$, ordinary viscous motion takes place (Fig. 1).

Experimental investigations of the motion of a structural debris flow carried out in a special flume showed that its resistance to motion is determined by the viscosity and density of the flow, and that, other conditions being equal (channel dimensions and characteristics), the velocity of motion of such a flow is always lower than the velocity of motion of a water flow

$$v_{\mathrm{s}} = v_{\mathrm{w}}(1 - a), \tag{4}$$

where a is an index taking into account the structural characteristics of the flow under consideration. According to our experimental data,

$$a = 0.09\sqrt{\eta_{\mathrm{e}} - \eta_0} - b(\gamma_{\mathrm{s}} - 1), \tag{5}$$

where η_{e} is the effective viscosity of the flow; γ_{s} is its unit weight; η_0 is the initial viscosity of the structural flow (~ 3 poise); $b = \mathrm{tg}(3\eta_{\mathrm{e}})$.

The experimentally obtained values of v_{s} are shown in Fig. 2.

Fig. 2. Curves of the dependence of the velocity of motion of a structural debris-flow mass v_{s} on the depth of flow h.
1 —water; 2 —$\eta = 2.5$ poise, $\gamma = 1.48$ g/cm^3; 3 —$\eta = 7.0$ poise, $\gamma = 1.31$ g/cm^3; 4 —$\eta = 7.0$ poise, $\gamma = 1.58$ g/cm^3.

At a velocity of motion somewhat lower than the velocity of a water flow, a structural debris flow has a significantly greater transporting capacity than a water flow. The capacity of a moving debris flow to transpo-

to maintain in suspension large heavy inclusions far exceeding the holding capacity of this same mudflow mass when in the static state, despite the destruction of the structure of the moving flow. This is explained by the fact that, during motion, the destruction of the structure occurs in the direction of motion of the flow. The absence of vertical destruction of the structure does not allow a heavy boulder to settle to the bottom. At the same time, the velocity gradient of the flow itself imparts motion to the boulder, and the lubrication between

Fig. 3. Curves of the dependence of the depth of the residual layer h_0 on the viscosity of the flow η_e and the slope of the channel i. 1—$\eta_\mathrm{e} = 3$ poise; 2—7 poise; 3—12 poise; 4—20 poise

Figure 3: Fig. 3. Curves of the dependence of the depth of the residual layer h_0 on the viscosity of the flow η_e and the slope of the channel i. 1—$\eta_\mathrm{e} = 3$ poise; 2—7 poise; 3—12 poise; 4—20 poise

the boulders and the mass of the flow facilitates motion. Thus, both factors—the tangential tractive force and the structural qualities of the flow—promote the transport of large inclusions by it.

Experimental studies have shown that, at values $\eta_\mathrm{e} = 7$ poise and $\gamma_\mathrm{s} = 1.58$ g/cm^3, a viscoplastic mudflow at a velocity of 2 m/sec is capable of transporting individual concrete cubes of weight Q 300-350 times greater than cubes moved by a water flow moving at the same velocity, and of weight 80-90 times greater than the mudflow mass could hold in a state of rest. As the viscosity and density of the flow mass increase, the ratio $Q_\mathrm{s}/Q_\mathrm{w}$ increases still further. The experiments also showed that large heavy bodies move in the flow with a velocity v_t, lagging behind the velocity of the flow itself all the more, the lower the viscosity of the flow and the larger the size (weight) of the inclusion; i.e., $v_\mathrm{s} - v_\mathrm{t}$ is directly proportional to the size of the heavy inclusion d and inversely proportional to the viscosity of the flow η_e. This lag does not depend on the magnitude of the flow velocity. In flows of considerable viscosity (dough-like consistency), $(v_\mathrm{s} - v_\mathrm{t}) \to 0$, and a transition to flocculated motion $(v_\mathrm{s} = v_\mathrm{t})$ is observed.

Fig. 3. Curves of the dependence of the depth of the residual layer h_0 on the viscosity of the flow η_e and the slope of the channel i.
1—$\eta_\mathrm{e} = 3$ poise; 2—7 poise; 3—12 poise; 4—20 poise.

In view of the presence of an initial shear resistance τ_0, a structured viscoplastic flow is characterized by a residual near-bottom layer h_0 (see Fig. 2), whose magnitude depends on the viscosity of the flow and the slope of the channel. When the motion of the flow ceases, the layer h_0 remains in the channel. Values of h_0 have been obtained experimentally for various values of h_0 and i (see Fig. 3).

Thus, a viscoplastic structured mudflow is a medium intermediate between a liquid and a solid body, possessing both certain properties of liquids (fluidity, continuity) and certain properties of solids (holding and suspending capacity with respect to heavy bodies, initial shear resistance).

The propositions set forth are obviously valid with respect to the motion not only of mudflows, but also of any hydrophilic viscoplastic media (concrete mix, clay solutions, etc.).

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Note: Figure translations are in progress. See original paper for figures.

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