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THE THEORY OF EXISTENCE OF DEBRIS-FLOW MIXTURE AS A KEY COMPONENT IN COMPUTING DEBRIS-FLOW CHARACTERISTICS

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It was established that the dependence between density of debris-flow mixture and minimum slope of the channel, such that the debris-flow mixture can move without stopping and disintegrating, is ambiguous. The theoretical and experimental researches made it possible to develop the basic model of debris-flow process which allows to compute the basic debris-flow characteristics (volume, discharge, density) all the way from the start to its stopping on the debris cone or in the mudflow-storages reservoir. Key component of this model is the theory of existence of debris-flow mixture by means of which the course of debris-flow process is determined (that is, if a debris flow moves it can be enriched by solid component or partially disintegrated).

During the last decades in Kazakhstan the principal direction of defence against debris flows was the construction of mudflow check-dams. The defence of potentially endangered areas requires reliable methods to assess behaviour of debris flows. However, only very crude methods are available at the present time. The theory of existence of debris-flow mixture can considerably improve quality of computation of debris-flow characteristics.

Debris flow modeling

For defence against debris flows the information on frequency, volume, discharge of debris flows, and density of debris-flow mixtures is required. If disastrous debris flows are of infrequent occurrence, the data on characteristics of debris flows can be obtained by means of modeling.

The model for computing the debris-flow characteristics includes the following blocks: critical conditions of debris-flow formation; entrainment of loose rocks enclosing a channel; granulometric composition of solid component of debris-flow mixture; viscosity; plasticity; density; velocity of debris flow; energy required for keeping of solid component in suspension; energy which can be expended by a flow for keeping of solid component in suspension; deposition of solid component; stopping of debris-flow mixture.

Initial information for computing the debris-flow characteristics are: morphometric characteristics of starting zones and debris flow path; granulometric composition of loose rocks, their density, porosity, and humidity; data on stability of loose rocks to erosion; dependence of Bingham yield stress of suspension (mixture of water and particles which sizes do not exceed 1 mm) on concentration of solid component; water discharge in the main channel and its tributaries.

As a result of computing data on volume, discharge, velocity of debris flow, density of debris-flow mixture, its viscosity and Bingham yield stress, granulometric composition of solid component of debris-flow mixture can be obtained at any site on the debris flow path.

Key components of the model are the blocks which allow to evaluate condition of debris-flow mixture. This means to define the trend of debris flow development because the density of debris-flow mixture can increase or decrease.

The simplest example of determination of debris-flow characteristics is the case when the resistance to the movement of the debris flow depends upon the plastic property of the debris-flow mixture and the Coulomb friction. Debris-flow mixtures the movement of which is conditioned by overcoming the Coulomb friction come to a halt on the slopes exceeding 15-20°. The mixtures where a solid component is kept in quasi-suspension due to plastic property can shift on relatively slight slopes. To set them in motion it is sufficient to fulfill the inequality

$$H > \frac{\tau_m}{\rho_m g \sin\alpha}$$

where H = flow depth; τ_m = Bingham yield stress; ρ_m = density of debris-flow mixture; α = channel slope angle; and g = gravitational acceleration.

The movement of debris-flow mixture in which the solid component shifts in suspension due to the stream energy is of theoretical and practical interest. In the course of a debris flow movement two processes can take place. Involving in a debris-flow formation loose rocks, enclosing a channel and a deposition of a solid component of a debris-flow mixture. These processes depend on morphometric characteristics of a channel, discharge, and volume of debris flow, density of debris-flow mixture, granulometric and mineralogical compositions of its solid component, rheological properties of the mixture. As a result the discharge, and volume of the debris flow can increase or decrease.

The progress of a debris flow is determined by the ratio between power required for keeping a solid component of a debris-flow mixture in suspension and power which the debris flow can expend for keeping a solid component in suspension. Keeping a solid component in suspension is achieved due to mixing up of a mixture caused by communication of a debris flow with the channel elements and also at the expense of energy of the turbulent mixing. Plastic property of a debris-flow mixture and Archimedean force can play an important role in keeping a solid component in suspension.

The conducted researches have proved that the dependence between limiting values of density of debris-flow mixtures and a channel slope can have an ambiguous nature [6, 7, 8]. It is caused by dependence between density of debris-flow mixture and a minimum gradient under which the mixture can shift without stopping and disintegrating which has a segment of a negative incline. A negative incline on this segment is the reason of a predominance of positive feedbacks over negative feedbacks. Positive feedbacks are conditioned by an increase of energy which can be expended by a flow for maintaining a solid component in suspension as the density of a debris-flow mixture is increasing. Negative feedbacks are conditioned by an increase of viscosity and plasticity of a debris-flow mixture having negative impact on mixing up is increasing.

Features of debris-flow formation

A wide range of water discharge, various humidity of soil, their mineralogical and granulometric compositions, morphometric characteristics of debris flow origin sites, etc. lead to various mechanisms of debris-flow formation. The features of debris-flow formation show themselves in change of the dependence between density of debris-flow mixture and the minimum gradient of the channel (called the Z-function) where debris flow during its movement does not stop (or does not disintegrate) and also the dependence between the maximum possible value of density and a gradient of the channel (called the Ξ-function).

A family of the Z-functions is shown in Figure 1. A family of the Ξ-functions corresponding to the family of the Z-functions is shown in Figure 2. It can be seen that the angular coefficient of tangents to the Z-functions is positive at the small flow depth (Fig. 1, curves H_1, H_2, H_3, H_4). This is due to intensive increase of viscoplastic resistance to movement of micro-flows caused by an increase of concentration of fine particles in a debris-flow mixture. The particles which maximum sizes only moderately exceed flow depth can take part in the micro-flows. The critical flow depth (H_{cr}) (at $H > H_{cr}$ the Z-function becomes ambiguous) is a complex function of density of a debris-flow mixture, mineralogical and granulometric compositions of its solid component, roughness of the channel. For typical soils of the Tien Shan a value of H_{cr} lies within the range of 0.3-1.5 m. If the flow depth is small (Fig. 1, curves H_1, H_2, H_3, H_4), even at small values of volumetric concentration of solid particles (0.1-0.3) viscosity and Bingham yield stress of two-phase mixtures reach values which exclude a possibility of considerable enrichment of micro-flows by solid component on slopes of 10-20°. As flow depth increases, rocks containing relatively coarse particles can be involved in the movement. It leads to sharp decrease (100-1000 times) of Bingham yield stress and viscosity of debris-flow mixtures at the same density of a debris-flow mixture. Increase of flow depth and relative decrease of effective viscosity are favourable for development of the turbulent mixing up. The result further increase of density of a debris-flow mixture is made possible. Under such conditions the Z-function becomes then ambiguous (Fig. 1, curves H_5, H_6, H_7).

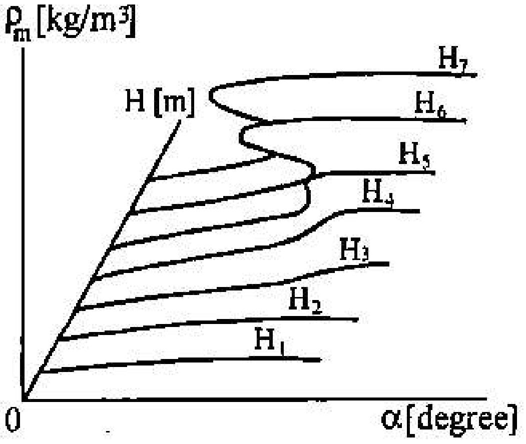

Figure 1. A family of the Z-functions

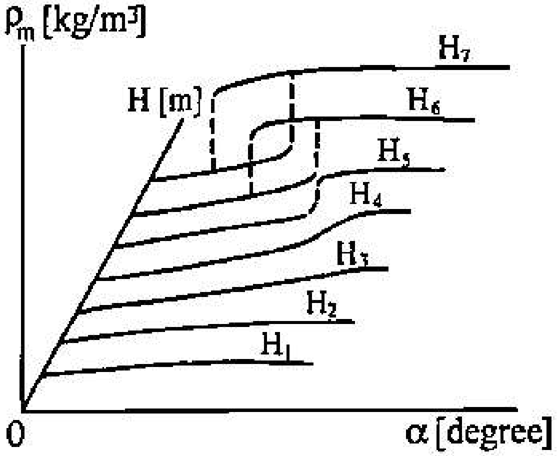

Figure 2. A family of the Ξ-functions

Let us consider in detail physical processes which determine a nature of a change of the Z-functions. In the course of movement of two-phase flows the shift of a solid component can be connected with energy expenditure for overcoming the Coulomb friction, a viscoplastic resistance, momentum transfer from particles to particles and from particles to the channel, suspension of solid particles. At the same density of a debris-flow mixture energy expenditure for performance of one or another work depends largely on mineralogical and granulometric compositions of solid component of a debris-flow mixture. So, if the solid component is represented with a clay, we can neglect energy expenditure of a flow for overcoming the Coulomb friction and suspension, because the velocity of settling such particles is small.

A limiting density of a debris-flow mixture formed as a result of the interaction of a flow with dust-clay fractions depends on erosive capacity of a flow. The value of a limiting density is much less than the value of density at which movement of a debris-flow mixture stops due to increase of its Bingham yield stress. Debris-flow mixture formed on the steep slope can shift further on a significantly slighter slope keeping its physico-mechanical features, provided concentration of a solid component of a debris-flow mixture does not exceed the values determined by the Ξ-function.

However, small dispersion of sizes of particles inherent to soil containing only dust-clay fractions, is not typical for the majority of the Tien Shan debris-flow dangerous regions. Soil having a large dispersion of sizes of particles (from colloidal particles to boulders) is typical for the Tien Shan. The participation of soils containing sand-pebble fractions in a debris-flow formation gives rise to a significant energy expenditure for suspension of solid particles. The value of the energy expenditure depends not only on concentration of a solid component of a flow, but also on the relative contents of fractions.

If composition of a solid component is polydisperse, the energy expenditure for suspension are described by the functions which are designated by 2 in Figure 3. The availability of the extremum in the above mentioned functions leads at certain conditions to a qualitative change in behaviour of the Z-functions. They become ambiguous. The relative positions of the curves, which describe the above mentioned energy expenditure as a function of density of a debris-flow mixture can be various, depending on mineralogical and granulometric compositions of soil. The following cases can take place:

a) soil consisting mainly of dust-clay fractions;
b) the granulometric composition of soil is characterized by the large dispersion of sizes of particles (Fig. 3);
c) the dispersion of sizes of particles is so large that energy viscoplastic resistance to movement appears when energy consumption for suspension becomes negligible.

The change of the relative positions of curves 1 and 2, as well as ordinates of extremums of curves 2 is the reason of a substantial change of the form of curves 3. So, if curve 3 is monotone in Figure 3a, the same curve 3 has an inflection point in Figure 3b, and in Figure 3c curve 3 which describes the energy expenditure for suspension of a solid component and overcoming visco-plastic resistance has two extremums (maximum and minimum).

The comparison of the above mentioned functions (Fig. 3) with the functions which describe the energy abilities of flows (Fig. 4) allows to take the Z-functions. The Z-function corresponding to curve 3 (Fig. 3b) is shown in Figure 5b; as can be seen the Z-function in Figure 5b has an inflection point unlike the Z-function shown in Figure 5a; and the Z-function shown in Figure 5c differs from Figure 5a even more. The most important feature of the Z-function shown in Figure 5c is the ambiguous relationship between slope and density of debris-flow mixture. A break in the Ξ-function (Fig. 2) is a consequence of ambiguity of the Z-function.

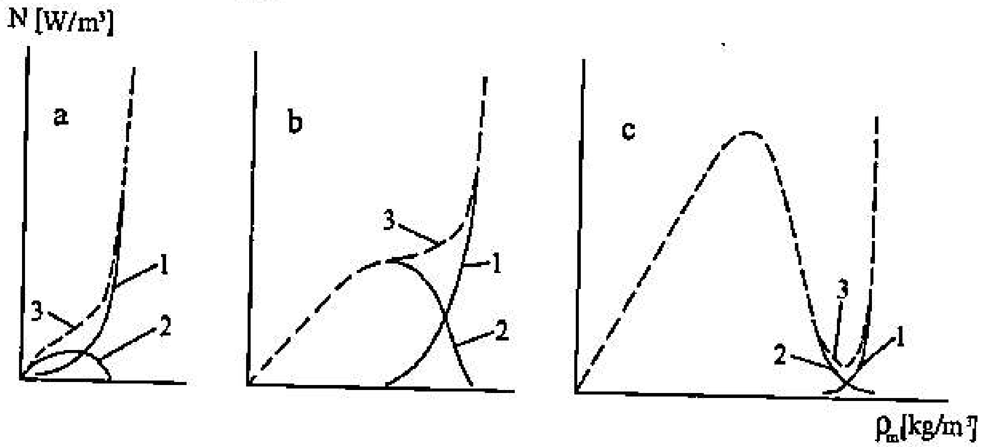

Figure 3. The graphs of functions which describe the energy expenditure for viscoplastic deformation (1), suspension of solid component of debris-flow mixture (2), the total energy expenditure (3). a - predominance of dust-clay fractions, b - predominance of sand-clay and sandy fractions, c - predominance of sand-rubble and boulder fractions.

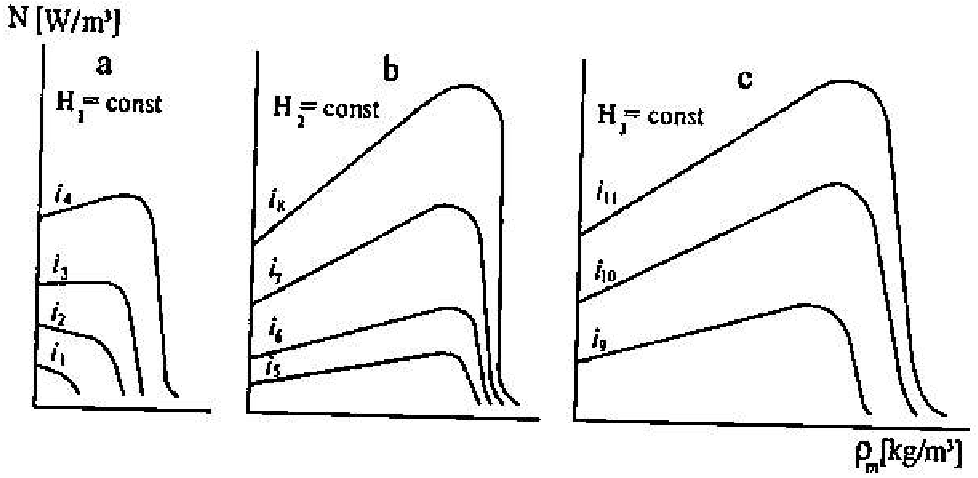

Figure 4. Curves which describe the energy consumption for suspension of a solid component depending on the density of a debris-flow mixture under various channel slopes (i) ($i_1<i_2<i_3<i_4$; $i_5<i_6<i_7<i_8$; $i_9<i_{10}<i_{11}$; $H_1<H_2<H_3$). The decrease of energy is caused by increase of viscosity and plasticity of a

debris-flow mixture.

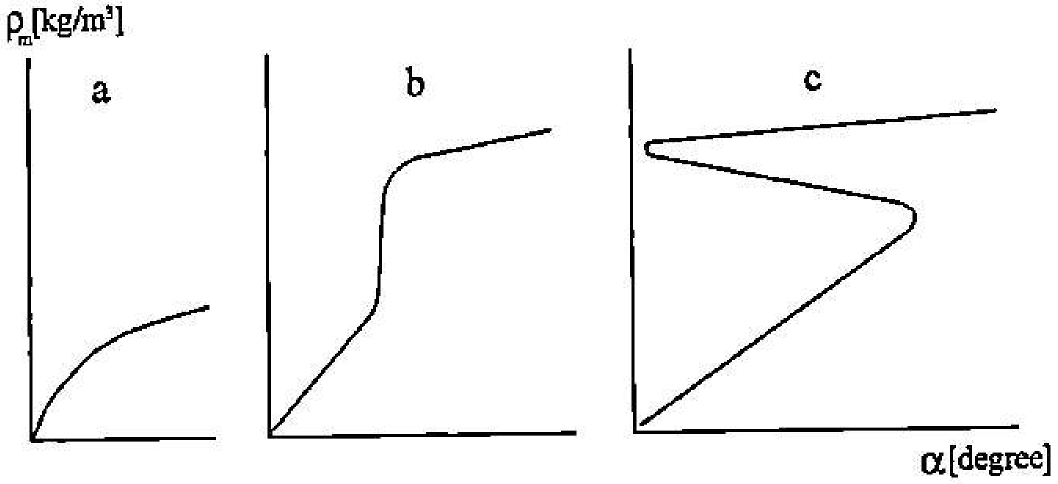

Figure 5. Equilibrium state curves which are received by the decision of the equations set which graphs are shown in Figures 3-4.

Use of equilibrium state curve for computation of debris-flow characteristics

The basic propositions of the theory are as follows: the state of a system «channel/debris flow origin site - debris-flow» is characterized by point (ρ_{mi}, α_i) located on the phase plane. The vector passing through this point indicates to a trend of a debris-flow process (Fig. 6). Theoretically there are two variants of an equilibrium state curve:

when the Z-function is unambiguous (Fig. 6a);

when the Z-function is ambiguous (Fig. 6b).

In Figure 6 area *I* is an area of enrichment of debris-flow mixture by solid material. Area *II* is an area of partial disintegration of a debris-flow mixture. If the system is characterized by point *M* located on the phase plane (area *I*) (Fig. 6b), then during the enrichment of a debris-flow mixture by solid material (at t → ∞) its density will be increase up to ρ_1. If the system is characterized by point *N* (area *I*), then the development of a debris-flow process will lead to the enrichment of a debris-flow mixture up to ρ_2. If the system is characterized by point *K* (area *II*), then a debris-flow mixture will disintegrate. This leads to decrease of density of a debris-flow mixture up to ρ_3. Equilibrium state, which is characterized by point *P*, is unstable (Fig. 6b). The slightest casual deviations of density from ρ_4 to one or another side lead either to further increase of density up to ρ'_4 or decrease up to ρ''_4.

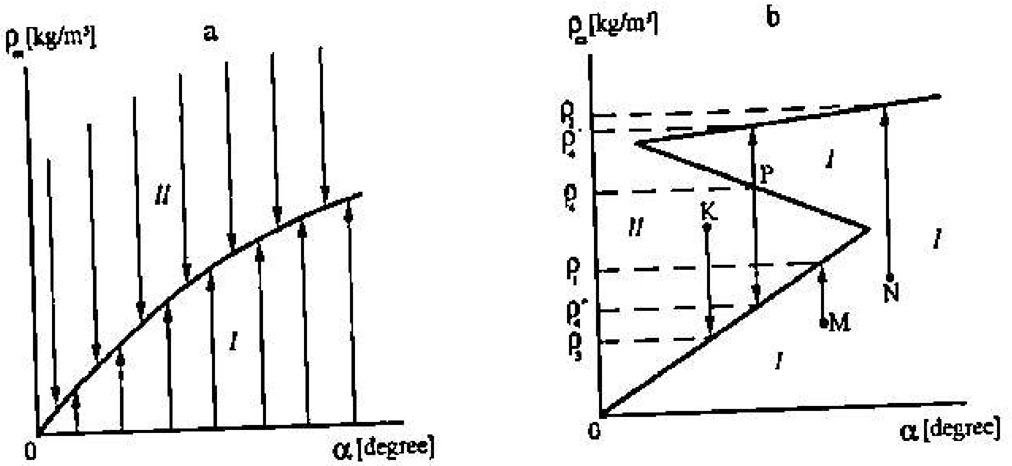

Figure 6. Equilibrium state curves located on the phase plane: a - unambiguous, b - ambiguous; I – area of enrichment of debris-flow mixture by solid material, II - area of disintegration of debris-flow mixture.

It is known that the Z-function (Ξ-function) is a generalization for debris-flow processes. Each point of the Z-function (Ξ-function) represents an equilibrium state of the system «channel /debris flow origin site - debris flow», that is, an asymptotic of the evolutionary equation $d\rho/dl = F(\rho, \alpha)$. The asymptotic of the evolutionary equation, in its turn, depends on flow depth, granulometric and mineralogical compositions of solid component.

Let us consider the change of the state of a system «channel/debris flow origin site - debris flow» on the phase plane and its influence on the course of debris-flow process. Let the condition of a debris-flow mixture is characterized by point $F(\alpha_1, \rho_1)$ located on the phase plane (Fig. 7a). Since, as it follows from the theory, the debris-flow mixture can exist even at a gradient of $\alpha_2 < \alpha_1$, the excess energy of the flow can be expended on involving additional portions of loose rocks into debris-flow process. Let density of a debris-flow mixture increase up to ρ_2 (point E), but for existence of a debris flow with density ρ_2 it is enough a gradient of α_3 ($\alpha_3 < \alpha_1$), etc. as long as the density of the debris flow increase up to ρ_3.

Applying the above mentioned reasonings about the debris-flow process in those cases when the initial value of density of debris-flow mixture falls in the area $OB\alpha_{cr2}$ it may be concluded that line OB represents the Ξ-function for the gradients of $\alpha < \alpha_{cr2}$. The Ξ-function corresponding to the area $OB\alpha_{cr2}$ is unambiguous and continuous. Further infinitesimal increase of a channel gradient leads to a finite change of the density of a debris-flow mixture, that is, the Ξ-function undergoes a break at $\alpha = \alpha_{cr2}$. The reason of the break in the Ξ-function arises from the change of a behaviour of the Z-function at $\rho_{cr2} < \rho_m < \rho_{cr1}$.

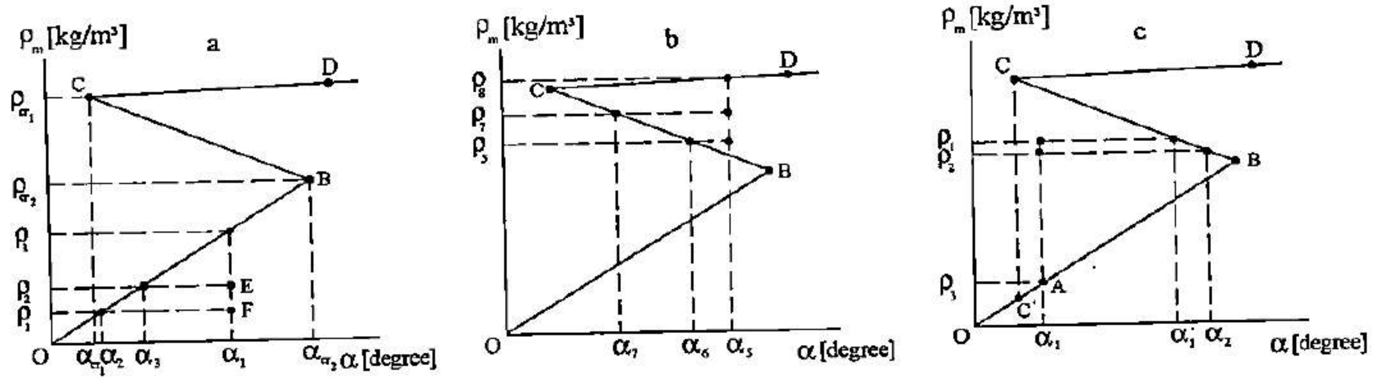

Figure 7. To defining evolution of debris flows (phases of debris-flow process).

The fact that the Z-function has a segment *BC* with a negative incline is of scientific and practical interest. The section $d\rho_m/d\alpha < 0$, under consideration shows that increase of density of a debris-flow mixture in the interval (ρ_{cr2} - ρ_{cr1}) makes for its further increase up to values of density corresponding to line *CD*. Most simply the above mentioned can be shown graphically. Let a state of debris-flow process be characterized by coordinates (α_5, ρ_5). Comparing conditions of debris-flow process with a position of line *BC* (Fig.7b), we come to the conclusion that the energy of a debris flow exceeds minimally required energy corresponding to point (α_6, ρ_5) for maintaining density of debris-flow mixture ρ_5. In the presence of loose rocks in the channel so much of excess energy of a flow, which depends on the value $\Delta\alpha = \alpha_5 - \alpha_6$, will be expended on increase of density of debris-flow mixture, for example up to ρ_7.

But at this stage the excess energy of a debris flow corresponding to $\Delta\alpha = \alpha_5 - \alpha_7$ increases. And at these conditions it will inevitably lead to further increase of density of debris-flow mixture, etc. as long as the density increases up to ρ_8.

Exactly the converse the debris-flow process develops in those cases when its state is characterized by coordinates of points lying in the area *OBC* (Fig. 7c). Let a state of a debris-flow process be characterized by coordinates (α_1, ρ_1). Comparing coordinates of a mudflow process with the position of lines *OB* and *BC*, we come to the conclusion that for existing the mixture with density ρ_1 without disintegration it is necessary that the debris flow move at a gradient of α'_1. As the energy of flow moving at a gradient of α_1 is not enough for maintaining density ρ_1, the partial disintegration of debris-flow mixture will happen which is accompanied by a decrease of its density, for example up to ρ_2; but for the debris-flow mixture with density ρ_2 to move without disintegration, it is necessary (as it follows from Fig. 7c) that the mudflow move at a gradient of α_2. As can be seen the deficit of energy still further has increased, resulting in a further decrease of density of debris-flow mixture, etc. until the density decrease up to ρ_3 which is a stable condition of a debris-flow mixture at the angle of α_1.

If the Z-function is represented as shown in Figure 6a, then debris flows with high density can exist only at significant gradients. If the Z-function is represented as shown in Figure 6b-7, then debris flows with high density can exist on relatively slight gradients. In the last case the Ξ-function has the form which is shown in Figure 8; it can be seen that the relationship between limiting density of a debris-flow mixture and a rate of a gradient is described by an ambiguous function.

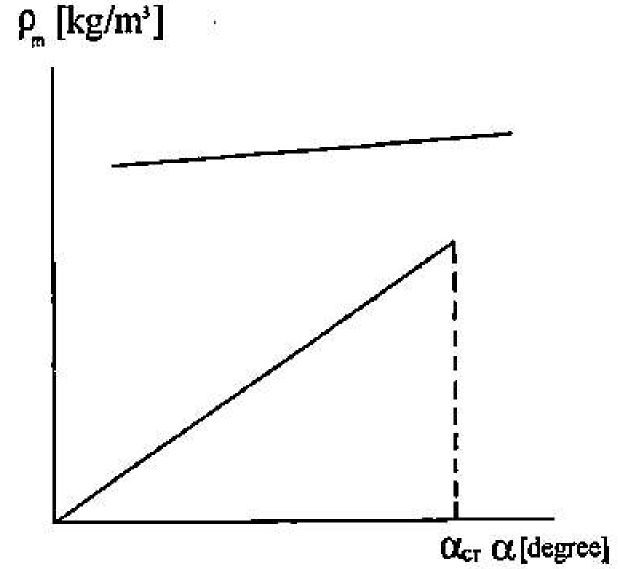

Figure 8. Graph of the Ξ-function corresponding to the ambiguous Z-function (the curve of stable conditions).

Conclusions

The researches have proved that the relationship between limiting values of density of debris-flow mixtures and channel gradient can have an ambiguous character. The theory of existence of debris-flow mixture allows to predict a trend of debris-flow processes in complicated cases, that is, when mixing debris flows with water flows take place, movement of debris flows at slight gradients, and during filling of mudflow-storages reservoirs.

The propositions of the theory of existence of debris-flow mixture are well agreed with the data of full-scale observations obtained during the artificial formation of debris flows at the Chemolgan test site during 1972-1991 [2, 3, 4, 9, 14], the data on the debris flows of 1963, 1973, 1977 in the Zailiysky Alatau [12], the debris flow of 1982 in the Dzhungarsky Alatau, the debris flow of 1988 in the Zhamankum desert [1].

Figure 9 shows the results of experiments made on linear and circular flumes [6]. The density of a debris-flow mixture depends on angle of inclination of a linear flume ambiguously. In nature the debris-flow mixture with density of 2300-2400 kg/m^3 will not form on slight slopes, but if it forms on relatively steep slope (11° and more), the debris-flow mixture can move without stopping and disintegrating on slope of 0.5-3°. Debris-flow mixture with density of 2300-2400 kg/m^3 formed in 1921 in the Malaya Almatinka River basin moved without stopping and disintegrating on slope of 3-5° for a distance of more than 15 km [11]. The debris-flow formed mainly on slope of 15-17°. Debris-flow mixture with density of 2300-2350 kg/m^3 formed in the Sarkand River basin in 1982 moved without stopping and disintegrating on slope of 1-5° for a distance of more than 25 km [10]. The formation of the debris-flow mainly occurred on slope of 10-11°. The debris-flow mixture with density of 2350-2400 kg/m^3 formed in the Issyk River basin in 1963 moved without stopping and disintegrating on slope of 5.5° for a distance of more than 7 km [13], and it formed mainly on slope of 18-20°. During the artificial formation of debris flows at the Chemolgan test site in 1975 the debris-flow mixture with density of 2300-2400 kg/m^3, which formed on slope of 16-17°, moved without stopping and disintegrating on slope of 3-5° (Fig. 9) [2, 5].

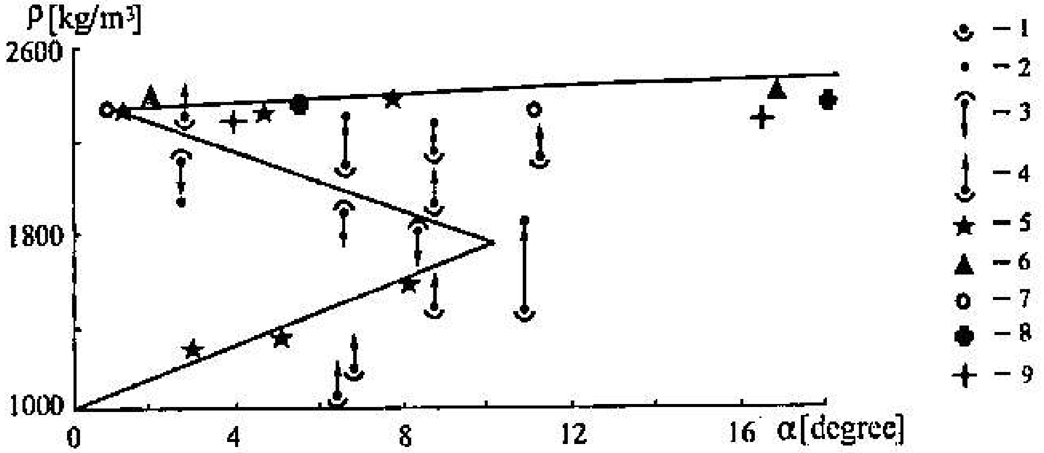

Figure 9. The results of experimental researches of equilibrium state curves: 1-initial value of density; 2- finite value of density; 3-disintegration of mixture; 4-enrichment of mixture; 5-data which obtained on the circular flume; natural data: 6-the Malaya Almatinka River basin, 1921; 7-the Sarkand River basin, 1982; 8-the Issyk River basin, 1963; 9-the Chemolgan test site, 1975.

The developed mathematical model of existence of debris-flow mixture adequately describes natural process and it is used in the basic model for computation of the basic debris-flow characteristics

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ТЕОРИЯ СУЩЕСТВОВАНИЯ СЕЛЕВОЙ СМЕСИ – КЛЮЧЕВОЙ ЭЛЕМЕНТ РАСЧЕТА ХАРАКТЕРИСТИК СЕЛЕЙ

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Было установлено, что зависимость между плотностью селевой смеси и минимальным уклоном русла, при котором селевая смесь может перемещаться без остановки и распада, неоднозначна. Теоретические и экспериментальные исследования позволили разработать базовую модель селевого процесса, позволяющую рассчитывать основные характеристики селя (объем, расход, плотность) на всем пути его движения вплоть до остановки на конусе выноса или в селехранилище. Ключевым элементом этой модели яв-

ляется теория существования селевых смесей, с помощью которой определяется ход селевого процесса (т.е. способен ли селевой поток по мере движения обогащаться твердой составляющей или произойдет частичный распад селевой смеси).

СЕЛ ҚОСПАСЫНЫҢ БОЛУЫ ТЕОРИЯСЫ – СЕЛДЕРДІҢ СИПАТТАМАЛАРЫН ЕСЕПТЕУДІҢ НЕГІЗГІ ЭЛЕМЕНТІ

Геогр. ғылымд. докторы Б.С. Степанов

Сел қоспасының тығыздығы мен өзен арнасының сел қоспасын тоқтаусыз және бөлмей ағызып отыратын минималды еңісінің өзара байланысының біркелкі еместігі анықталды. Теориялық және эксперименттi зерттеулер сел процесінің селдің ысырынды конусында немесе сел қоймасында тоқтауына дейінгі бүкіл қозғалыс жолындағы негізгі сипаттамаларын (көлемін, шығынын, тығыздығын) есептеуге мүмкіндік беретін негізгі үлгісін жасауға жол ашты. Бұл үлгінің негізгі элементі – сел қоспаларының болуы теориясы. Оның көмегімен сел процесінің жүруі(яғни сел ағысының өз жолында қатты қосындылармен баюы немесе сел қоспасының жартылай бөлінуі мүмкіндіктері) анықталып отырады.