CrossMark

ORIGINAL PAPER

The experimental debris flows in the Chemolgan river basin

T. A. Vinogradova[1,2] (iD) · A. Yu. Vinogradov[2,3]

Abstract Debris flows are one of the most dangerous and common hydrological phenomena in mountainous regions. They are extremely various in their type and character, but they are always mountain flows consisting of a mixture of water and loose-fragmental debris. The problem of calculation and forecasting the mudflows still remains intractable. There are several reasons for that: Firstly, the representatives of the whole spectrum of the Earth Sciences (Hydrology, Geology, Geomorphology, Geography, Mechanics, Rheology) deal with this problem from their point of view. Secondly, systematic monitoring of passing debris flows are currently held only in several countries only (USA, Canada, Austria, Switzerland, Japan, China), because they require significant funding. Thirdly, the calculation methods, having been accepted for the present time, give certain errors. In this article, the results of the artificially triggered debris flow experiments conducted in 1972–1976 in the Chemolgan river basin, organized by the Kazakh Research Hydrometeorological Institute are described. These were the first full-scale experiments with the detailed recording of the numerous debris flows characteristics ever conducted. The movie is attached as supplementary material to the Editorial of the Special Issue. The information about the used measurement equipment, the obtained characteristics of debris flows, the debris flow classification accepted as a result of the experiments is given. Conducting such experiments in nature allowed us to assess various aspects of the formation of these natural phenomena and made it possible to build the mathematical models of the debris flow processes.

Keywords Experimental debris flows · Chemolgan river basin · Vinogradov

✉ T. A. Vinogradova
   vinograd1950@mail.ru

1   Saint-Petersburg State University, Saint Petersburg, Russia

2   Science Production Union Hydrotekhproekt, Saint Petersburg, Russia

3   Saint-Petersburg State Forestry Engineering University, Saint Petersburg, Russia

 Springer

I am going to cite a far worthier thing—
the master of all the master's experience.

…neither of human investigations can claim to be the genuine science if it does not use mathematical
proves.

Leonardo da Vinci

1 Introduction

Irregularities on the Earth's surface represent the space within which the processes of rock destruction and the gravitational movement of the products of this destruction down to the plain are intensive. The overall picture is complicated by the presence of water which in liquid and solid form together with loose-fragmental debris participates in the process of such natural movement.

The physical laws that govern the overall process of the mass movement are known, but it is really difficult to estimate the effect of simultaneous impact of different kinds of factors. This happens because of the limitations of our knowledge when it comes to the rarely observed phenomena such as debris flows.

Despite the fact that the research work devoted to study of the debris flows and to the methods of their numerical modelling has been conducted for more than a century, the efficiency of mitigation measures is still often insufficient. This situation is due primarily to shortage of reliable actual data on the characteristics of the debris flows. The main features of debris flows are the unexpectedness of their occurrence, short duration, and great destructive power. This leads to the difficulty in direct observation of the phenomenon. So far, most methods of debris flows parameters estimation have been based on the study of the traces left by the former debris flows. The reliability of such data is too high.

In this connection, the data obtained as the result of the direct observation of the phenomenon is very important.

The laboratory experiments on the debris flows have been carried out by Van Steun and Coutard (1989), Holmes et al. (1990), Yang et al. (2011), Turnbull et al. (2015), etc.

Observations of the parameters of periodically coming debris flows have been reflected in publications of Curry (1966), Suwa et al. (1973), Suwa and Okuda (1983), Gallino and Pierson (1984), Savage and Lun (1988), Arratano et al. (1997), Genevois et al. (2000), Parsons et al. (2001), Lin et al. (2004), McArdell et al. (2007), Holmes and Over (2008), Shieh et al. (2009), Yang et al. (2014), etc.

However, there are not many results available from the full-scale experiments due to the problems with creation of a large debris flows in natural conditions.

The experiments on simulation of natural full-scale debris flows in Nature were carried out by Vinogradov in 1972–1975 in Zailiyskiy Alatau near Alma-Ata and provided opportunity to get unique data (Rickenmann et al. 2003). The results of these experiments stimulated the development of the debris flows science in the USSR in 1970s–1980s.

As the result of the experiments four main directions in the future research have been developed:

(1) Construction of the theory of the debris flow processes and methods of numerical modelling;
(2) Construction of the basic principles of the debris flows mitigation measures;

(3) Development and implementation of the debris flow observation methods and the automated system of terrestrial and remote sensing monitoring of the debris flow processes for their forecasting and prevention;

(4) Study of geological and hydrological regime of the debris flow basins.

2 Description of the experimental design

Khonin drew attention to the large debris flow trench located in the upper reaches of the Chemolgan river in 50 km in a straight line from the former capital of Kazakhstan—Alma-Ata after a careful aerial study of the possible choices for a suitable sites of debris flow formation (Vinogradov 1980a, b). The Chemolgan river basin borders on those in the West on the Uzunkargaly river, in the East on the Kaskelen river stretching from South to North in the form of a strip of 30 km long (Fig. 1).

At an altitude of 2300 m the valley of the river is blocked by a ledge, which is accepted as an extent of the maximum glaciation. It separates erosion–denudation and glacial landforms from each other. The ledge goes into a steep-slope land—plateau—folded Quaternary glacial formations above 2900 m. The plateau contains closed basins separated by the low hills, on one of which a lake is bordering a debris flow basin (Fig. 2).

Potential debris flow body (PDFB) inclines the loose-fragmental debris mass which theoretically could be carried out by a debris flow in hollow way. It made up 160 m

Fig. 1 The view of the Chemolgan debris flow channel bed (Google Earth)

Fig. 2 The catchment area of the debris flow from a satellite image (Bing maps)

Fig. 3 Geographical location of the experiment

altitudinal range, the area of the loose-fragmental debris mass was 35,000 м², and the average power was 10 m (Fig. 3).

Lake basin located at an altitude of over 2900 m was closed by a dam unit with spillways designed to create water releases with a maximum flow rate of 100 m³/s. The total volume of the reservoir was 73,000 m³.

The debris flow hotbed was located in the steepest part of the ledge of Quaternary moraines in the interval of heights of 2644–2900 m. The length of the debris flow trench was 930 m, the area—70,400 m^2. The slopes of the trench sides ranged from 35 to 800 m. The average depth of the debris flow trench reached up to 45 m, the maximum one—75 m. The maximum width of the trench was 150 m, and the volume was 3.17 million m^3.

Below the hotbed (2644 m) there was the debris flow channel constrained by bedrock outcrops forming several waterfalls. The tortuosity of the channel in that area was about 1.3 which created rough flow turbulence. The total length of the channel was 760 m with an average slope gradient of 11.50. At the altitude 2484 m the channel ended in a waterfall, with a height of 12 m, which belonged to the lower trench.

The lower trench had a length of 510 m with a slope gradient of 7.50 and ended at the confluence of the Left Chemolgan river. Still below there was a debris cone of an average width of 150 m, maximum—260 m, with an average gradient of 50.

In the lower part of the debris flow channel in 1.7 km from the dam unit a control debris flow measurement section line was equipped. Above the control section line the construction to measure the dynamic impact of debris flow on the obstacle was built. The height of the middle part of the construction was 1.2 m with a width of 0.6 m. It was a concrete monolith with the front part lined with 4 mm steel sheet with dynamometrical cylinders installed. The strain sensors were designed for the impact of 6×10^5 N force. In the first second of the experiment the impact force exceeded the measurement limit and the dynamometers were disabled. In the experiment of 1973 the recording equipment was installed in a safe place on the shore of the channel and the information from the sensor was transmitted via radio transmitter working in the range of medium waves. With the passage of the debris flow, the device was providing the information for about 1 min, which allowed to determine the value of the debris flow front part density, made up 2300 kg/m^3. Later the concrete structure was destroyed, it happened in 1972, and the device was carried away by the flow.

To measure the dynamic pressure inside the flow, an aluminum ball with a diameter of 0.5 m and a mass of 186 kg was attached in the watercourse on the massive anchor with 18-mm steel cable with the length of 30 m. Traction on the cable link was designed for impact of 105 N. Under the flow impact the cable was torn.

All the attempts to measure the density of debris flow by scooping the mudflow mass with a measuring vessel proved to be ineffective. Only after debris flow wave declined the sample was successfully taken. Therefore, since 1973 the pressure sensors have been used to measure the density of the debris flows. For contactless measurement of the density, the gravimetric and the radio wave methods have been applied. A magnetometric method of the debris flow density measurement was also developed.

The seismic signal device was designed by the Special Construction Office of the Science Production Department "Geophysics" under the guidance of Dr. B. S. Stepanov (Stepanov and Zukerman 1983). The device was not destroyed by the passing debris flow and was providing the information about the runoff and the velocity of a flow movement continuously during the entire debris flow process. Adding to the instrument of a signal device sensor of level and density, it was possible to obtain a robust, compact system for obtaining the information about the most important characteristics of debris flows and warning of the debris flow hazard.

3 The debris flow events

On the whole there were five experimental runs. The first experiment was conducted on August 27, 1972. Maximum water discharge runoff was 16 m³/s, its volume was 12,000 m³, and the maximum runoff of mudstones flow reached 120 m³/s, 32.8 thousand m³ of loose-fragmental debris sediments passed through the control debris flow measurement section line. The average density of the debris flow was 2070 kg/m³.

The features of the motion of the mudstone flow obtained in practice were not quite consistent with the "generally accepted" ideas of those times. For example, the density of debris flow is high, but the flow is roughly turbulent and not "structural" or "coherent." The movement is pulsing, but there are no congestion and their breakouts.

When observing from the top, it is a thick, viscous (creamy) mass. On the surface of mudstone flow, there is a significant number of boulders and the depth of the flow way is more than their diameter. This can be considered as a symptom of a high-density mudflow. Large boulders slowly rotate and turn over during their movement. Their speed is less than the speed of the flow.

The second experiment on the Chemolgan debris flow site took place on August 22, 1973. There have been three water releases (Table 1) with 3-min intervals and the last one was the longest and with a constant runoff. During the experiment 102,000 m³ of loose rock were floated out from the debris hotbed. The maximum density of debris flow mixture measured by quantum magnetometer reached 2300 kg/m³, and the average density of the flow was 2120 kg/m³. The increase of the characteristics of this mudstone flow compared with the first experiment was associated with the regime of the releases one after another with breaks that have disrupted the equilibrium of the potential debris flow solid mass (Table 2).

The third experiment was conducted on August 19, 1975. There were two water releases with the initial water volume in the reservoir of 60,000 m³. Consistently two powerful mudstone flows passed at the intervals of 50 min. The mudstone flow of 1975 was not only the largest of the experimental debris flows but also the most spectacular.

Vinogradov (1980a, b) described the movement of the second front wave of the debris flow with enthusiasm as impressive since the material was behaving "like a battering RAM (…)" rushing down the channel "in the vanguard of the huge piles of boulders a stone

Table 1 Water release parameters

The year of experiment	No. of water release	Duration (min)	Volume, thousand (m³)	Maximum runoff (m³/s)
1972	1	18.5	11.8	16.0
1973	1	2.5	1.7	16.2
	2	10.0	7.3	15.8
	3	9.0	5.3	12.1
	4	222	24.9	2.1
1975	1	6	10.0	28.0
	2	6	5.0	15.0
1976	1			5.0
1978	1			9.0

Table 2 Debris flow parameters

The year of experiment	Volume, thousand (m^3)	Average density of flow (kg/m^3)	Height of waves (m)	Average velocity (m/s)	Maximum runoff (m^3/s)
1972	41.8	2070		9.0	120
1973, release 1–3	63.3	2120			100
1973, release 4	72.8	1970			18
1975	72.0	2160	4.0	6.3	380
1976	18.0	2200	2.0	4.5	45
1978	13.0	2400	2.8	4.3	130

block, a large 7-m axis of which coincided with the direction of the flow movement." The stone block jutting and protruding out of the front wave for approximately 3 m was being dragged over the dry boulders of the floodplain below the control section line. This movement was accompanied by haze arising from blows of the stone block on large boulders. The haze was clearly visible in individual frames of the film with their frame-by-frame viewing. Apparently, therefore, the motion of mudstone flow including its formation in the hotbed is accompanied by decomposed-haze odor.

In the wide valley of the Chemolgan river the front of the flow was gradually released from large boulders and had the average velocity on the upper 5-km stretch (5–60) 4.0 m/s, on the lower one 18 km (3–40) and 1.9 m/s.

On November 8, 1976, the fourth small experiment was held in autumn of 1976. Due to a late period the reservoir was able to accumulate only 13.2 thousand m^3 of water. Therefore, the maximum flow of the discharge was only 5 m^3/s and the maximum debris flow was 45 m^3/s. In addition to measurement of characteristics of mudstone flow the new equipment was tested.

On September 9, 1978, the fifth experiment was carried out. The maximum flow runoff was 9 m^3/s, debris flow runoff was 130 m^3/s. The debris floe passed the area in the section line with a length of 134 m with an average speed of 4.3 m/s.

As a result of the experiments the information about the physical processes happening during the rock mass involvement into the debris flow was obtained. This allowed us to create a mathematical model of a debris flow process called transport-shear one.

4 Mathematical model

The debris flow process that takes place in the conditions described above is defined as a transport-shear one.

When constructing the model, we use the following concepts and provisions:

1. The coefficient of instability of the PDFB as the reciprocal value of the well-known in soil mechanics and engineering Geology coefficient of loose-fragmental debris mass slope stability. In this case the coefficient is determined for PDFB as

$$K = tg\alpha / tg\varphi$$

2. Elementary potential flow capacity (ability to produce job per unit of track per time unity W/m = kg m/s^3).

$$U = g \left[Q \rho_0 + (\xi \rho_0 + \rho) G \right] \sin \alpha$$

3. The index of mudflow mass mobility

$$R = \frac{Q}{G} + \xi - \Theta_{nn},$$

where Q/G is the ratio of water and solid rock substance runoffs in a mudstone flow moving over the thalweg of a debris flow hotbed. ξ—relative humidity of PDFB (the ratio of volumetric moisture content by volume fraction of solids in a potential debris flow body of a debris flow hotbed); Θ_{nn}—the same ratio but at the limit of a mixture of water and rock fludity (in the first approximation is taken equal to 0,133). The formation and movement of debris flow is meant to stop when $R \leq 0$. In the mountains one can often see such "stalled debris flows" especially on extensive screes where the amount of water involved in such developments is almost always limited. Let us assume the following situation: the increment of the flow rate of the solid material involved in an incipient mudflow as it moves through the riverbed of debris flow hotbed is directly proportional to the above three arguments:

$$\frac{dG}{dl} = A \cdot K \cdot U \cdot R = A \left(\frac{tg\alpha}{tg\varphi} \right) g \sin \alpha [Q\rho_0 + (\xi\rho_0 + \rho)G] \left(\frac{Q}{G} + \xi - \Theta_{nn} \right)$$

here A—is the coefficient of proportionality (m s^2/kg); l—distance over a thalweg; α—the angle of inclination of a debris flow hotbed bedplate containing the PDFB; φ—the angle of internal friction of damp rock (static) composing the PDFB; Q—water flow runoff into the debris flow hotbed (m^3/s); G—solid substance (rocks) runoff in a debris flow (m^3/s).

Let us transform the equation as follows:

$$\frac{GdG}{[Q\rho_0 + (\zeta\rho_0 + \rho)G][Q + (\zeta - 0,133)G]} = A \frac{tg\alpha}{tg\varphi} g \sin \alpha dl$$

And further

$$\int_{G_0}^{G} \frac{GdG}{[Q\rho_0 + (\zeta\rho_0 + \rho)G][Q + (\zeta - 0,133)G]} = A^{tg\alpha}/_{tg\varphi} g Sin\alpha \int_{l_0}^{l} dl$$

After the necessary integration, the following result is obtained:

$$l = \frac{\left[\frac{Q\rho_0}{\zeta\rho_0 + \rho} \ln \frac{Q\rho_0 + (\zeta\rho_0 + \rho)G}{Q\rho_0 + (\zeta\rho_0 + \rho)G_0} - \frac{Q}{\zeta - \theta} \ln \frac{Q + (\zeta - \theta)G}{Q + (\zeta - \theta)G_0} \right]}{A \frac{tg\alpha}{tg\varphi} g Sin\alpha [Q\rho_0(\zeta - \theta) + Q(\zeta\rho_0 + \rho)]} + l_0$$

The basic calculation equation is solved not relatively to the sought function G but to the argument l which causes some inconvenience. But the primary solution of the equation is a really basic computational procedure. As a result, we have a dependency G on the track length of the forming debris flow during its progress through the thalweg of debris flow hotbed.

The results of the model calculations are shown in Table 3 where they are compared with the measured values.

Table 3 Comparative results of calculations

Year of the experiment	1972	1973, release 1–3	1973, release 4	1975	1976	1978
Maximum measured	120	100	18	380	45	130
Maximum calculated	118	109	18	241	43	81

As for the coefficient of proportionality, on the basis of the data obtained during artificial reproduction of debris flows under natural conditions it is in the range $A = (3\text{–}5) \, 10 - 6 \, m \, S^2/kg$. It needs further clarification for each individual basin.

5 Conclusion

Experiments on the Chemolgan river have extended our knowledge of debris flow processes, allowed us to understand more clearly the differences between the two major debris flow processes: transport-shear and shear ones. The Chemolgan river experiments allowed us to create a mathematical model of a transport-shear process. On the basis of the observed differences in the development and course of the transport, transport-shear, and shear debris flow processes, it became possible to make the separation of debris flow phenomena into flows of low and high density. In the first case there is a transport of carried and suspended sediments. The conditions of formation and movement are almost identical. The whole channel is the formation zone.

As a result of processing the data of experiments on the Chemolgan polygon the information about the character of dependence of the eroding debris flow mixture ability on its density and composition of the solid phase was obtained for the first time. When mixture density is 1300–1400 kg/m^3 erosive ability of the mixture reaches its maximum. With the growth in viscosity of the suspension the percussion impact of large particles reduces, in a similar way the pulse of speed and pressure on the border between the flow and the channel changes; consequently erosive capacity of debris flow mixture reduces. The sharp increase in the viscosity of the debris flow mixture at a density of 2400–2500 kg/m^3 reduces the eroding ability to a minimum.

Experimental reproduction of the natural mudstone flows, measurement of their characteristics, photos and filming have shown the features of formation of debris flow sediments formation. So, two or three tiers of superimposed (leaning) terraces are formed during the passage of a large flow the surface of which experiences undulations with a total fall of level.

Mathematical model of transport-shear debris flow process developed by Vinogradov (1980a, b) is consistent with the actual observed characteristics of mudflow processes and thus can be used for engineering calculations and forecasts.

The experiments on the Chemolgan debris flow polygon allowed us to see and measure something that previously was only possible to guess about or to build speculative models which were not always representative. These works were the first steps to the experimental debris flow hydrology.

References

Arratano M, Deganutti AM, Marchi L (1997) Debris flow monitoring activities in an instrumented watershed on the Italian Alps. In: Chen CL (ed) Proceedings of the 1997 1st international conference on debris-flow hazards mitigation: mechanics, prediction, and assessment; San Francisco, CA, USA. ASCE, New York, pp 506–515

Curry RR (1966) Observation of alpine mudflows in the Tenmile Range, central Colorado. Geol Soc Am Bull 77(7):771–776. doi:10.1130/0016-7606(1966)77[771:OOAMIT]2.0.CO;2

Gallino GL, Pierson TC (1984) The 1980 Polallie Creek debris flow and subsequent dam-break flood, East Fork Hood River basin, Oregon (USGS open-file report 84–578). U.S. Geological Survey, pp vi + 59

Genevois R, Tecca PR, Berti M, Simoni A (2000) Debris-flows in the Dolomites: experimental data from a monitoring system. In: Wieczorek GF, Naeser ND (eds) Debris-flow hazards mitigation: mechanics, prediction, and assessment. Proceedings of the second international conference. AA Balkema, Rotterdam, pp 283–291

Holmes RR, Over TM (2008) Assessment of flood Remediation with minimal historic hydrologic data: case study for a small urban stream. 4th international symposium on flood defence (ISFD4) on flood defence, managing flood risk, reliability, and vulnerability, Toronto, Ontario, Canada, 6–8 May 2008. http://ifi-home.info/isfd4/docs/May8/Session_1030am/Room_C_1030/Boneyard_Flood_defence_mtg_5_2008_holmes.pdf

Holmes RR, Westphal JA, Jobson HE (1990) Mudflow rheology in a vertically rotating flume. Proceedings of the international symposium on hydraulics/hydrology of arid lands and 1990 national conference on hydraulic engineering, San Diego, CA, USA. ASCE, Boston, pp 212–217

Lin CW, Shieh CL, Yuan BD, Shieh YC, Liu SH, Lee SY (2004) Impact of Chi-Chi earthquake on the occurrence of landslides and debris flows: example from the Chenyulan River watershed, Nantou, Taiwan. Eng Geol 71(1–2):49–61. doi:10.1016/S0013-7952(03)00125-X

McArdell BW, Bartelt P, Kowalski J (2007) Field observations of basal forces and fluid pore pressure in a debris flow. Geophys Res Lett 34(7):L07406. doi:10.1029/2006GL029183

Parsons JD, Whipple KX, Simoni A (2001) Experimental study of the grain-flow, fluid-mud transition in debris flows. J Geol 109(4):427–447

Rickenmann D, Weber D, Stepanov B (2003) Erosion by debris flows in field and laboratory experiments. In: Chen CL (ed) 3rd international conference on Debris-flow hazards mitigation: mechanics, prediction, and assessment; Davos; Switzerland; 10 Sept 2003 through 12 Sept 2003, vol 2. Millpress, Rotterdam, pp 883–894

Savage SB, Lun CKK (1988) Particle size segregation in inclined chute flow of dry cohesionless granular solids. J Fluid Mech 189:311–335. doi:10.1017/S002211208800103X

Shieh CL, Chen YS, Tsai YJ, Wu JH (2009) Variability in rainfall threshold for debris flow after the Chi-Chi earthquake in central Taiwan. Int J Sediment Res 24(2):177–188. doi:10.1016/S1001-6279(09)60025-1

Stepanov BS, Zukerman IG (1983) K modeli erozionno-sdvigovogo selevogo protsessa [Toward a model of erosion-shear debris flow process. In: Selevye potoki [Debris flows], Iss. 7. Gidrometeoizdat, Moscow, pp 39–46 (**in Russian**)

Suwa H, Okuda S (1983) Deposition of debris flows on a fan surface Mt. Yakedake, Japan. Zeitschrift fur Geomorphologie, Supplementband, 46, pp 79–101

Suwa H, Okuda S, Yokoyama K (1973) Observation system on rocky mudflow. Bull Disaster Prev Res Inst Kyoto Univ 23(3/4):59–73

Turnbull B, Bowman ET, McElwaine JN (2015) Debris flows: experiments and modelling. Comptes Rendus Phys 16(1):86–96. doi:10.1016/j.crhy.2014.11.006

Van Steun H, Coutard JP (1989) Laboratory experiments with small debris flows: physical properties related to sedimentary characteristics. Earth Surf Process Landf 14(6):587–596. doi:10.1002/esp.3290140614

Vinogradov YB (1980a) Etyudy o selevykh potokakh [Sketches on debris flows]. Gidrometeoizdat, Leningrad, p 144 (**in Russian**)

Vinogradov YB (1980) Transportnyi i transportno-sdvigovyi selevye processes. Model' so sredotochennymi parametrami [Transport and transport-shear debris flow processes. The model with lumped parameters]. In: Selevye potoki [Debris flows], Iss. 4. Gidrometeoizdat, Moscow, pp 3–20 (**in Russian**)

Yang QQ, Cai F, Ugai K, Yamada M, Su ZM, Ahmed A, Huang RQ, Xu Q (2011) Some factors affecting mass-front velocity of rapid dry granular flows in a large flume. Eng Geol 122(3–4):249–260. doi:10.1016/j.enggeo.2011.06.006

Yang QQ, Su ZM, Cai F (2014) DDA Simulations of large flume tests and large landslides triggered by the Wenchuan earthquake. J Appl Math Phys 2(6):359–364. doi:10.4236/jamp.2014.26043