INTRODUCTION

The full-scale experiments on the replication of debris flows were carried out by the Kazakh Institute for Hydrometeorological Research in the period from 1972 to 1978. To verify the development theories of debris flows, it was necessary to have data on the characteristics of actual debris flows. The characteristics of debris flows, presented in the publications, were usually derived from surveys of their traces. They are frequently unreliable. Because of the complication of creation of replication of debris flows, close to actual ones on scale, the laboratory simulation of debris flows were only performed. However, the lack of reliable criteria for the similitude of the models to the actual debris-flow process, it was not possible to use the results obtained for understanding the laws of formation and movement of natural debris flows.

To uncover the mechanism by which actual debris flows are formed an experiment had to be conducted on a scale making possible a debris flow with a discharge of 100 m$^3$/s and more because at smaller scales it is improbable that large boulders, which comprises about half the spectrum of the grain-size composition of the debris-flow deposits, would be entrained in the debris-flow process.

EXPERIMENTAL SITE

The experimental site is located in the Zailisky Alatau Mountains, about 50 km southwest of Almaty, in the Chemolgan River basin. This river basin extends from the south to the north in the shape of a narrow strip 30 km in length. In the upper part of the Chemolgan River basin there are several glaciers. Glacier run-off was accumulated in an artificial reservoir located at an elevation of 2900 m a.s.l. This reservoir was equipped with a gate to create an artificial flood. The maximum storage volume of reservoir was about 80 000 m$^3$. During the experiments carried out in the period from 1972 to 1978, the released water volume varied from 3600 to 40 600 m$^3$ (Khonin et al. 1976).

Below the reservoir, at an elevation from 2644 to 2900 m, there is a torrent gully. Its length was 930 m, the mean depth was 45 m and the maximum – 75 m, the mean slope was 16º. The total volume of the torrent gully was 3.17 million m$^3$. The gully is situated in an ancient moraine. Morphometric characteristics of the torrent gully, thickness and granulometric composition of soil create conditions for the formation of a large number of debris flows in the gully. The granulometric composition of soil in the first torrent gully presented in Table 1 (Vardugin 1976).

<table>
<thead>
<tr>
<th>Size of fractions (mm)</th>
<th>10 000-5000</th>
<th>5000-2000</th>
<th>2000-1000</th>
<th>1000-500</th>
<th>500-200</th>
<th>200-100</th>
<th>100-50</th>
<th>50-20</th>
<th>20-0.05</th>
<th>0.05-0.01</th>
<th>0.01-0.005</th>
<th>0.005-0.002</th>
<th>&gt;0.002</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>11.5</td>
<td>9.5</td>
<td>6</td>
<td>5</td>
<td>14</td>
<td>27</td>
<td>8.4</td>
<td>0.3</td>
<td>0.2</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Below the torrent gully there are a torrent channel and the second (lower) torrent gully (Figure 1). The length of torrent channel was 760 m, the mean slope of $11^\circ 30'$. Characteristic of the torrent channel are numerous outcroppings of bedrock forming more than 10 waterfalls at different heights. The bedrock outcroppings stabilize the channel, impeding its deformation during the movement of the debris flow. On the other hand they increase the bending of the channel (the coefficient of bending is 1.3) causing violent turbulence in the debris flow. In the sections between the bedrock outcroppings that form the waterfalls loose-debris deposits are intensively entrained by the flow. Thus, the debris-flow formation process would to a considerable extent continue to develop in the torrent channel if it was not impeded by the numerous outcroppings of bedrock.

At a height of 2484 m the channel is broken up by a stepped waterfall up to 12 m in height, which morphologically can be considered part of the lower gully. The region of the waterfall is almost an undeformable section and is suitable for carrying out debris-flow measuring observations. A debris-flow measuring site for monitoring a “control” cross-section was set up at this place (Khonin et al. 1976).

The length of the lower gully was 510 m. The mean slope of the second torrent gully was $7^\circ 30'$. It is probable that when this gully was formed debris flows occurred in it but they ceased with the decline in the longitudinal slope of the thalweg. At the present time the lower gully is a continuation of the torrent channel in which the debris flow becomes transformed and the debris-flow deposits are redistributed.

### 2.1 Measurement instrumentation

To determine the characteristics of debris flows the contactless devices were used during the experiments. The design department at the “Kazgeofizpribor” instrument making plant developed these devices in the period from 1968 to 1972. There are inventor’s certificates for all methods and devices used in the experiments.

These are the following devices:

- a two-frequency Doppler meter (radiowave length of 3 cm): the level and surface velocity of debris flows were determined;
- a seismic flowmeter: the discharge and average velocity of debris flows were determined;
- a quantum magnetic gradiometer (the interpretation of the data obtained by its made it possible to determine the average density of debris flow in a volume of $300–500 \text{ m}^3$).

In addition, motion picture filming of the debris flow on 35-mm colored negative film was employed during the experiments. Sixteen motion picture cameras were located at various places in 1972 and 8 in 1973.
Measuring instruments were located above the torrent channel. As the channel was in bedrock, its characteristics practically unchanged during the experiments conducted in 1972, 1973, 1975, 1976 and 1978.

3 MAIN RESULTS

In the period from 1972 to 1978 five experiments were conducted. The most large artificial debris flow was reproduced in 1975. The change in water level in the reservoir and the hydrograph of water releases from the reservoir are shown in Figure 2 (Khonin et al. 1977).

![Figure 2: Change in water level in the reservoir (1) and hydrograph of water releases from the reservoir (2)](image)

Figure 3. gives the results of measurements of density of debris-flow mass by magnetometric means. This same figure gives a hydrograph of the debris flow. The plot shows relative time, and the time at which the water outlets in the dam are opened is taken for the start of computation.

![Figure 3: Hydrograph of debris flow (1), change in magnetic field intensity with time (gamma) (2): a – first water releases, b – second water releases](image)
The peak discharge of the first water releases was 27.5 m$^3$/s. The peak discharge of debris flow during the first water release was 430 m$^3$/s, density debris-flow mass of 2300±100 kg/m$^3$, the maximum size of particles in the debris-flow mass of 8 m (Khonin et al. 1977).

3 CONCLUSIONS

As a result of the conducted experiments it was established:
If the slope of the debris flow origination site exceeds 17º and the water discharge of more than 6 m$^3$/s, and the granulometric and mineralogical compositions of rocks are as in the Zailisky Alatau, the interaction of a water flow with loose-rock leads to the formation of debris flow with density of 2400 kg/m$^3$.
The main mechanism for the entrainment of loose-rock in the debris-flow process is erosion.
The debris flow moves wavy.
The jams were not observed.
The deposition of debris flow occurs when the depth of debris flow becomes smaller than the size of the large particles.
The results of the conducted experiments, laboratory and theoretical studies allowed to reveal ambiguous dependence of ultimate density of debris-flow mass on channel slope (debris flow path) as well a possibility of a discontinuous increase (or decrease) debris-flow mass density when bed slope excesses (or decreases) a critical value. This allows to develop methods for calculating changes in characteristics of debris flow as it moves in a mountain valley and on a fan, to assess the risk of economic activity in debris flow hazardous areas, and to develop optimal measures to reduce damage caused by debris flows (Stepanov et al. 2017).

REFERENCES