Imitation Modelling of Influence of Relief of Mountain Slope on Destructive Ability of Snow Avalanches

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Abstract. The paper proposes a simulation model of avalanche snow mass movement based on the particle dynamics method. The total volume of snow mass is broken down into separate elements which can be either interconnected by certain forces or move independently of each other subject to prehistory. For the purposes of consistency of primary mechanical properties of snow mass, the interaction of its elements is commonly supposed to be viscoelastic. Viscoelastic interaction of snow mass elements makes it possible to take into account, while modeling, the ability of snow mass to disintegrate. A computer program was written in Object Pascal language in Borland Delphi 7.0 integrated programming environment to run multiple computer experiments with the model with the subsequent studying of the impact of primary physical and mechanical properties of snow mass on intensity of its down-slope movement. The model was verified by comparing of computer calculations of avalanche pressure and experimental data. The model curve agrees well with the experimental curve. The average model-experiment variation is approximately 7%.

1. Introduction
The snow avalanche meets different natural obstacles and man-made infrastructure facilities when moving downslope. The obstacles are exposed to avalanche action, which causes load take-up, displacement or destruction. In the paper, we consider such obstacles as buildings and constructions. The detailed experimental research into how obstacles of different type, shape and physical properties interact with avalanche is highly complicated. Avalanching occurs unexpectedly, the process of interaction with an obstacle is rapid, and it is difficult to record and measure the action of snow mass onto an obstacle. Therefore, the simulation computer modeling can be highly useful and helpful in studying of avalanche interaction with obstacles [1-5]. Avalanche movement and interaction with obstacles cover a wide class of physical phenomena, which requires the development of a universal mathematical model. The particle methods, in particular, the particle dynamics method and the SPH method (Smoothed Particle Hydrodynamics) are currently the most relevant and universal methods to model environments prone to fragmentation [6-8]. The method of modeling used in the paper refers to the particle dynamics method.

2. Model Foundations
The model takes into account the impact of external factors and effects on snow mass, slope geometry, mechanical movement of separate snow-mass elements (flakes), their elastoplastic interaction,
thermodynamic processes taking place inside snow mass and modifying the properties of individual snow elements [9-11].

In the model, snow precipitated on slope is represented by a population of a large number of separate round elements [12]. The state of each snow element \( i \) is determined by four variables: Cartesian coordinates of its center \((x_i, z_i)\) and two velocity components \((v_{xi}, v_{zi})\). The interaction of snow elements with each other and with the slope and obstacle is considered to be viscoelastic. The restoring force acts between the connected elements in model when they move apart from each other to a limit distance. The stress occurring when snow slabs break away is the physical interpretation of the above. Depending on whether the elements are bonded together or not, whether it is a strong or a weak bond, different formulas are used to calculate the force.

During modeling, the evolution of snow mass shall be traced, and the combined action of snow elements on an obstacle shall be determined. Therefore, it is necessary to calculate the trajectory of each snow element. The trajectories of elements are determined based on a solution to system of equations of individual elements motion, which can be written in accordance with the laws of motion. It is a set of motion equations for all \( N \) elements, which describes the evolution of snow mass in time. The flowchart of a model-implementing algorithm is given in Figure 1.

![Flowchart of Program Algorithm to Model Avalanche Action on Light-Weight Structure](image)

Figure 1. Flowchart of Program Algorithm to Model Avalanche Action on Light-Weight Structure.

To make studying of the equations system convenient, a computer model was written for modeling of building displacement and overturning by avalanche action in Object Pascal language in Borland Delphi 7.0 integrated programming environment, which is designed for carrying out of multiple computer experiments with a model and studying of the impact of primary physical and mechanical parameters of
snow mass on the intensity of its down-slope movement.

The building used in the model is treated as a single non-deformable object capable of spatial movement under the impact of snow avalanche. The two-dimensional model variant is quite suitable for the description of down-slope building movement and overturning relative to one of the ribs of a parallelepiped-shaped building. In this case, a light-weight structure on a post foundation is considered. This approach allows for the use of model with minor modifications to analyze the avalanche interaction with different vehicles and infrastructure elements. By setting different destruction limits and friction forces in bearing points, it is possible to reproduce different types of motion under avalanche impact in model, for example, only overturning without displacement (at high friction coefficient) or only displacement without overturning (at low friction coefficient).

The motion of building in space x–z is described based on Newton’s second law and the basic law of rotational motion dynamics:

\[
m_1 \frac{d^2 x_j}{dt^2} = \sum_{j=1}^{N_j} F_{x_{j}} - F_{TrL} - F_{Trp};
\]

\[
m_1 \frac{d^2 z_j}{dt^2} = \sum_{j=1}^{N_j} F_{z_{j}} + F_{TrL} + F_{Trp} - m_1 g;
\]

\[
J_z \frac{d^2 \phi_j}{dt^2} = \sum_{j=1}^{N_j} M F_{z_{j}} , + M F_{TrL} + M F_{Trp} + M F_{FL} + M F_{FP} , + M F_{rL} + M F_{rP} ,
\]

where \( m_1 \) and \( J_z \) – building weight and its moment of inertia relative to the center of gravity; \( x_j, z_j \) and \( \phi_j \) – Cartesian coordinates of the building and its inclination; \( F_{x_{j}}, F_{z_{j}} \) – components of force of interaction of snow element \( j \) with the building; \( M(F_{z_{j}}) \) – moment of force specified relative to the building center of gravity; \( F_{TrL}, F_{Trp} \) – friction forces in the weakest point of foundation securing the building from horizontal displacement; \( F_{TrL} \) and \( F_{Trp} \) – forces acting on the building from the left and right bearing points of foundation; \( M(F_{TrL}), M(F_{Trp}), M(F_{Fl}), M(F_{FP}) \) – moments of the abovementioned forces relative to the building center of gravity.

The straight slope with an embankment, which the building is located on, is selected as a terrain [13, 14].

The computer experiment with a model of avalanche interaction on building was carried out as follows. At some reference time, the building was located on an embankment of the specified height and was firmly secured to the bearing surface in foundation-simulating points. The snow mass at reference time was located on the slope at the specified height in the form of 0.6 m thick and 100 m long rectangular slab. During the computer experiment, the snow mass started to move downslope and, at a certain time, the avalanche front reached the building (Figure 2). Within a short period of time, the force action of avalanche reached the maximum, which could cause the building tearing-off from the foundation and its further movement by either displacement with insignificant inclination or building overturning, or the combination of the above variants of motion. The depression between the slope and building embankment significantly influences the nature of avalanche action. It can direct the snow flow in different ways, for example, throw it up, act on the upper part of the building or cause swirling. Therefore, it is necessary to determine, among other input parameters, the influence of depression shape. **Influence of Building Elevation Above Slope.**

A set of computer experiments was carried out to study the above effect in detail; the building elevation above slope \( h_{zd} \) varied from –1.0 to 3.0 m in increments of 0.5 m (Figure 2). Parameter \( h_{zd} \) was set so that at zero value of \( h_{zd} \) the slope transformed to an even site with no depression. At negative values of \( h_{zd} \) the building was not elevated above the slope and was located, quite to the contrary, in the slope hollow.

It was found that the landform in front of the building significantly influences the indicators of damaging avalanche effect. For example, at 0.6 m thick snow cover and 30° angle of slope, overturning of the building was guaranteed for all values of \( h_{zd} \) not exceeding 1 m (Figures 3, a, b).
The horizontal action force and, correspondingly, the side pressure at 0.5 m above the building footing reached their maximum values at $h=0$. However, starting with $h_{zd} = 2$ m, the avalanche action caused little if any displacement and significant inclination of the building. Such essential dependence of damaging action on the shape of depression or projection in front of the building can be explained as follows. The highest damaging action is caused by the lower part of avalanche with the height of 0.6...1.2 m. If the building is located on an embankment (Figures 2, a, b), then, the lower part of avalanche acts on the embankment, and the most part of avalanche energy dissipates in the depression in front of the building. However, if there are no depressions in front of the building (Figures 2, c, d) or if the building “sinks” in the slope

![Image](image-url)

**Figure 2.** Building Condition at the Moment of Highest Avalanche Action at Different Building Elevation Above Slope $h_{zd}$.

![Graphs](graphs-url)

**Figure 3.** Influence of building elevation above slope $h_{zd}$ on value of horizontal displacement $L_{cm.m}$ of building (a); maximum building inclination $\varphi_{h.m}$ (b); maximum horizontal force $F_{bok}$ acting on building (c), pressure at 0.5 meters above building footing (d).
(Figure 2, e), the lower part of avalanche acts directly on the building, which leads to much more expressed displacement and inclination. Thus, it is feasible to locate buildings at mountain slopes in such a way that there was a depression, not less than 3 m deep, between the building and the slope, where the most part of avalanche energy would dissipate. The location of buildings in terrain depressions is highly hazardous, as the avalanche layer with the highest energy will act directly on the building [15, 16].

3. Verification of Model Developed
The model was preliminary verified along the height-pressure distribution profile. The transverse pressure profile, \( P/P_{\text{max}}(h) \), was calculated in the proposed model of snow avalanche (Fig. 4, continuous curve). Here, \( P \) – pressure of snow mass moving to a building located at height \( h \). \( P_{\text{max}} \) – maximum pressure level. An experimental curve obtained at A.F.Lipatov avalanche impact device (Moscow State University) was used for comparison [17]. The device was 2.1 m wide and projected above slope surface for 9 m. Each shock sensor included two steel discs, 30 cm diameter each. The outer disc had three cones made of hardened steel. Based on the diameter of impressions left when cones were impressed into a duralumin plate secured to the inner disc, the maximum pressure was determined with an element of uncertainty, as the cone impressions depended not only on the impact pressure of blocks impinging on the device, but also on the number and frequency of impacts. Over the past years, dozens of powerful avalanches with the maximum impact pressure of up to 1,070 kPa, which is equivalent to 110 t/m\(^2\), have run into the device. The dashed line in Figure 3.9 shows the distribution of impact pressure with height available from the experiments. The primary impact action of dry avalanches is concentrated in the lower two-meter layer. The maximum impact occurs at 1.3 m, and the pressure recorded above and below this height decreases sharply.

The model curve agrees well with the experimental one. The average variation between the model and the experiment amounts to approximately 7%. In general, the peak in the model is slightly wider, which is possibly connected with higher fragmentation of the model snow mass. Moreover, the model dependence, \( P/P_{\text{max}}(h) \), declines faster within 1.5-5.0 m range, and snow elements are almost not observed above \( h = 5 \) m. It is probably connected with the fact that the element in the model is of considerably large weight so that it can go up the slope to the height exceeding 5 m.

![Figure 4. Dependence of Snow Avalanche Pressure on Elevation above Slope Surface.](image)

The validity of snow avalanche model is also confirmed by macroscopic features of avalanche, in particular, by the dependence of avalanche path length and angle of slope. To verify the model, the statistical data on 110 snow avalanches at Trans-Caucasian road shelf has been processed [18-20].

4. Appendices
The simulation model of avalanche snow mass movement has been proposed based on the particle
The algorithm has been built to calculate the mechanical impact of avalanche on infrastructure elements, and the computer program implementing this algorithm has been drawn. The model has been verified by using the experimental and statistical data. It has been shown that the elevated location of infrastructure elements at some height above the slope surface allows for damping of devastating impact of snow avalanche.

5. References

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