Model and algorithms of interaction of the snow avalanche with the stirrable and destructible obstructions

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Abstract. A model for studying the movement of avalanche-hazardous snow masses based on the method of smoothed particles is presented. This approach has been shown to be most appropriate in modelling environments prone to fragmentation. The impact of the snow avalanche on vehicles and the dependence of the affecting factors on the thickness of the snow cover and the terrain have been investigated. It has been found that with snow cover thickness up to 0.5 m, avalanche does not lead to loss of vehicle controllability. The results of the modelling at a qualitative level coincide with the real effects of the avalanche on the vehicle, which confirms the adequacy of the model developed.

1. Introduction
Recently there appears a lot of information on the increase of the natural cataclysms on the Earth. These include numerous earthquakes, floods, hurricanes, typhoons, tornadoes, avalanches and others. Each of these natural phenomena does not remain unnoticed in the scientific world. A real disaster in the mountain terrain is snow avalanches.

The works on the study of snow avalanches in Russia began starting from 30-th of the 20-th century. In the study of Revyakin V.S., the first detailed engineering-glaciological avalanche zoning of Altay region was employed. Tushinskii G.K. performed mapping of the avalanche-hazard areas, Blagoveshchenskii V.P. investigated specific features of avalanching in Khibini Mountains and at the West Caucasus. A large empiric material is presented in the works of Dunin A.K., Voytkovskii K.F., Bozhinskiy A.N., Losev K.S., Bolov V.R. The study of mechanics of snow motion as well as simulation of avalanches is given in the works by Saatchyan G.G., Grigoryan S.S., Yadroshnikov V.I., Kazakov N.A. and others. Experience in the study of avalanches abroad is mainly presented in the works of American, Swiss, French and Japanese experts: E. Adams, R. Hefeli, M. de Carven, V. Amman, R. Bolognese, K. Jaccard, A. Sato.

In order to simulate motion of the avalanche-hazard snow mass in the work a method of Smoothed Particles Hydrodynamics (SPH) was applied which is a gridless Lagrangian numerical method. Smoothed Particles Hydrodynamics technique is known to be well applied for the description of the processes of high-speed collision especially in the case when a considerable change in topology of the
model objects takes place (recession or an intensive agitation of a substance). This method allows simulating of the flows with strong deformations between the boundaries in the calculated area and, besides, it enables the changes of the connectivity within the area of simulation.

No information concerning connections between the mesh points is required for simulation that allows simplifying of the task and to eliminate tracing of between them. SPH-technique was applied for mathematical simulation of the landslides and tsunami (Khvostova O.E., Kurkin A.A.).

Snow avalanche sliding along the flank of a hill (or mountain) during its way down meets different natural obstacles and objects of infrastructure built by the people. Obstacles in the form of vehicles, as well as the buildings and constructions are considered within the frames of this work. Detailed experimental studies of how the obstacles of different kind, shape and their physical characteristics interact with the avalanche are really strongly impeded. Avalanching occur quite unexpectedly, the process of its interaction with an obstacle is galloping, the effect of a snow mass on the obstacle is difficult to fix and to measure it in a quantitative manner.

Therefore, the use of the imitation computer simulation technique for the study of interaction between avalanche and the obstacles seems to be rather actual one.

2. The objective of the investigations
The objective of the investigations is an improvement of the mathematical models describing dynamics of the interaction of a snow avalanche with the stirrable and destructive obstacles in order to solve the practical tasks for providing of the required safety level in the avalanche-hazard regions.

In the process of simulation all of the bulk of snow mass is dissected into separate elements that move according to the laws of classical mechanics and interact with each other by viscous-elastic forces. The state of each of the snow elements \(i\) is determined by four variables: Cartesian coordinates of its center \((x_i, z_i)\) and by two components of velocity \((v_{xi}, v_{zi})\).

The shape of the flank hill and initial location of the vehicle and snow avalanche is determined by the following design diagram (Figure 1).

![Figure 1. Presentation of the flank surface in the mode, vehicle and a snow avalanche.](image)

In order to describe mechanical motion of the vehicle in \(x−z\) section (in a cross-section) we used second Newton law (in each of Cartesian directions), as well as the main law of the rotary motion dynamics:
\[
\begin{align*}
\frac{d^2 x_V}{dt^2} &= \frac{N}{m_V} E_{xj-V} + F_{CF} - F_{FrL} - F_{FrR}; \\
\frac{d^2 z_V}{dt^2} &= \frac{N}{m_V} E_{zj-V} + F_{WhL} + F_{WhR} - m_V g; \\
J \frac{d^2 \phi}{dt^2} &= \sum E_{j-V} \left( F_{WhL} + F_{WhR} + F_{FrL} + F_{FrR} \right),
\end{align*}
\]

where \( m_V \) and \( J_V \) are mass of the vehicle and its moment of inertia relative to the center of gravity (point \( C \)); \( x_V, z_V \) and \( \phi_V \) are Cartesian coordinates of the vehicle and its tilt angle; \( E_{xj-V} \) and \( E_{zj-V} \) are components of the force of interaction for \( j \)-th element of snow with the vehicle; \( M(F_{Ey-V}) \) is a moment of force relative to the center of gravity; \( F_{CF} \) is centrifugal force in case of the vehicle motion along a road turn; \( F_{FrL}, F_{FrR} \) are friction forces holding left and right wheels from the displacement in horizontal direction perpendicular to the direction of the vehicle motion; \( F_{WhL} \) and \( F_{WhR} \) are the forces effecting on the vehicle from suspensions of the left and right wheels; \( M(F_{FrL}), M(F_{FrR}), M(F_{WhL}), M(F_{WhR}) \) are moments of the presented forces relative to the vehicle center of gravity (point \( C \)).

In the process of simulation geometrical area representing the vehicle changes its position in space. In order to define spatial arrangement of the vehicle surfaces interacting with the snow mass as well as of the wheels interacting with the bearing area for each step of integrating, \( \tau \) computation of coordinates is performed for the coordinates of reference points \( P_1 \) - \( P_6 \) in the following way:

\[
\begin{align*}
x_{P_i} &= x_v + r_i \cdot \cos(\phi_i + \phi_t); \\
z_{P_i} &= z_v + r_i \cdot \sin(\phi_i + \phi_t),
\end{align*}
\]

where \( x_{P_i} \) and \( z_{P_i} \) are coordinates of the point \( P_i \); \( x_V \) and \( z_V \) are coordinates of the vehicle center of gravity; \( r_i \) and \( \phi_i \) are polar coordinates of the point \( P_i \) relative to the vehicle center of gravity in its equilibrium state.

Between the snow element and the body of the vehicle there appears force interaction if a center of the circle-element turns out into the area apart from the body of the vehicle by the distance of \( d_{g/2} \).

For each step of integrating, \( \tau \) it is required for every element \( I \) to determine if it is arranged into geometric region designating the vehicle and to determine the distance of the element incorporation \( r_{in} \) into the body of vehicle as well as the direction of effecting force \( (n_x, n_z) \).

In case of the direct contact the force effect of the element on the vehicle body is calculated according to the following system of equations:

\[
\begin{align*}
F_{xj-V} &= -c_0 \left( \frac{d_{g/2}}{2} - \sqrt{(x_s - x_{p_2})^2 + (y_s - y_{p_2})^2} \right) \frac{x_s - x_{p_2}}{\sqrt{(x_s - x_{p_2})^2 + (y_s - y_{p_2})^2}}; \\
F_{zj-V} &= -c_0 \left( \frac{d_{g/2}}{2} - \sqrt{(x_s - x_{p_2})^2 + (y_s - y_{p_2})^2} \right) \frac{y_s - y_{p_2}}{\sqrt{(x_s - x_{p_2})^2 + (y_s - y_{p_2})^2}}; \\
M(F_{Ej-V}) &= F_{xj-V} (y_{p_2} - y_v) + F_{zj-V} (x_{p_2} - x_v).
\end{align*}
\]

As a result of checking the ingress for each element into the vehicle region and calculations of the corresponding force impacts one can obtain summation force effect of the snow mass on the vehicle body thus resulting in the change of its mechanical state.
3. Results and discussion

The model presented above is rather highly universal and it allows studying the influence of a great number of the avalanche parameters, terrain relief, the vehicle itself on the impact of avalanche on the vehicles.

When snow avalanche comes in contact with the vehicle body the latter one undergoes a strong force impact (Figure 2).

Duration of the impact is about 20 seconds but the greatest force effect is observed at the avalanche front, approximately 2–3 seconds later after beginning of the contact between the snow and the vehicle. Maximum of the force effect is attained for about 2 seconds and after that it is gradually reduced with avalanche exhaustion and filling the vehicle with snow.

Thickness of the primary snow cover was taken as one of the parameters for snow avalanche at the flank of the hill, $h_{sn}$; it determines the intensity of the effect for snow mass and its total volume. In order to study the effect of $h_{sn}$ onto the damaging factors of snow avalanche a series of computer experiments was accomplished where $h_{sn}$ varied from 0,5 up to 1,1 m with a step of 0,1 m.

For low $h_{sn}$ the flood of snow mass is not so significant to deliver a dangerous effect on the vehicle (figure 3, a). For $h_{sn} = 0,5$ m the displacement of the vehicle in fact does not take place (figure 3, a), while its tilt angle is no more than 1–3º (figure 3, b). For the mean value of the snow cover thickness (1,0 m) the effect of avalanche results in a displacement and a significant tilt of the vehicle (figure 4, b). However, tip-over of the vehicle does not take place. But under a large value of $h_{sn}$ due to a high kinetic energy of the snow mass flood the vehicle turns over and it is thrown off the road.

Analyzing the dependence of $\phi_{tilt}(h_{sn})$ it is possible to conclude that if a thickness of snow cover is less than 0,7 m the tilt of the vehicle is nearly negligible (it is less than 5º), for the cover thickness of 0,7 to 1,1 m a significant tilt of the vehicle (by 10–30º) can be seem, however, it does not lead to turn-over and beginning from $h_{sn} = 1,1$ m a turn-over of the vehicle, in fact, takes place (figure 3, b).

![Figure 2](image-url) Dependence of the force $F$ on the time $t$ effecting on the vehicle in a horizontal direction.

![Figure 3](image-url) The effect of the snow cover thickness $h_{sn}$: on the value of lateral displacement of the vehicle $L_{displ \_max}$ (a); angle $\phi_{tilt \_max}$ of the maximum vehicle tilt (b).
Thus, for the thickness of snow cover less than 0.5 m snow avalanche does not result in a loss of the vehicle steerability, for the thickness of 0.5 to 1.0 m it leads to the loss of steerability but it does not cause the vehicle turn-over and its throwing off the road, but for the thickness of more than 1.0 m the result is turning off the vehicle and the latter can be thrown off the road.

Results of the simulation qualitatively coincide with the real consequences of avalanche effect on the vehicles and this means adequacy and relevance of the developed model.

4. Conclusion
Thus, the model of interaction between snow avalanche and a vehicle was developed which made it possible to study the character of this interaction, to predict the damages (turn-over and displacement of the different vehicles, to offer measures directed at the decrease of the probable turn-over and a considerable displacement of the vehicle. Computer program was elaborated implementing the proposed model of interaction between avalanche and the vehicle, allowing to investigate specific features of this interaction, to predict the possible damage effects and to choose an efficient avalanche-protection structure.

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