Methods for prediction of the avalanche danger

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Abstract. The work considers methods for the prediction of the avalanche danger. It shown that for the local forecasts the most efficient way is to simulate snow mass by the particles dynamics technique. Basin on this model it is possible to predict the critical parameters for the avalanche sliding, the character of motion of snow mass, the force and energy of its impact on the movable and immovable obstacles with different shape and, hence, a destructive avalanche ability.

1. Introduction
Long-term experience in the study of avalanches enabled to reveal certain regularities in the process of the avalanche formation, to discover major factors of avalanche failure and to estimate parameters of this phenomenon [1]. Avalanches failure occurs under instability of the snow slab on the mountain descent caused by the impact of some external factors and the process inside snow depth proceeding under the effect of external factors. An avalanching can occur at the descents with a slope angle greater than 15° and at the depth of snow cover more than 15 cm. However, these cases are quite rare. To detect the areas where avalanches can be formed while mapping the patterns of the mean and low scale their borders are lined along isolines of snow cover equal to 30 cm, while isolines for 70 cm snow cover limited the areas where avalanches are formed quite frequently and thus they are considerably dangerous. [2]. Most favorable for the avalanching are recognized the descents where the slope angle is of 25-40° [3-5]. The detailed large-scale investigations with the use of full-scale observations and calculations, the study of geomorphological, geobotanical, soil and hydrological features in the different regions make it possible to detect the territories where formation, motion and stopping of avalanches happens.

2. Avalanche hazard forecasts
Nowadays three kinds of the forecasts concerning avalanches danger are applied — background small-scale for the mountain territory, background large-scale for the mountain pool or a group of avalanches path and the detailed one for a certain avalanche path or avalanche-prone descent (local forecast).
Avalanche forecast presumes early determination of a certain time interval when snow accumulation and metamorphism processes can result in the instability of a snow cover and avalanche formation. It is closely connected with the forecast of meteorological conditions, such as the kind, intensity of snowfalls, drift-snow transport due to snowstorms, temperature and air humidity, and other characteristics of meteorological conditions have a direct effect on the state and stability of the snow cover.

Background forecast includes the assessment of the avalanche danger in the considered mountain district and it is issued in the form of “avalanche-threatening” or “non-avalanche-threatening”. Advance time in the avalanche forecasts is limited by the absence of the quantitative techniques for the long-term forecast of the precipitation intensity, intensity and duration of thaw and other meteorological factors in the mountain terrain. Very often the forecast is issued with “zero” advance time, meaning only the current assessment of the avalanche danger.

Local forecast provides the determination of stability coefficients for snow cover in the place of avalanche initiation for a certain avalanches path and the time before the assumed spontaneous avalanching, assessment of the probable volume and length of avalanche debris, the choice of optimal conditions for the elimination of avalanche danger by the artificial avalanching.

Most well-developed background avalanche forecast is that one for the avalanches caused by snowfalls and snowstorms. Certain successes are achieved in the development of the background forecasts for the avalanches from the slush mainly based on the analysis of snow-meteorological environment and the defined statistical dependences between the time of occurrence of the avalanche danger and the change of factors determining avalanching. At this stage of analysis all of the available data on the structure, density and temperature conditions of the snow cover and local characteristics of its stability.

Methods of the local forecasts are only weakly developed that is caused by the absence of a technique and equipment for obtaining of reliable information on the state and properties of snow cover in the areas of avalanche origination while accuracy of the existent ways for the determination of the strength properties in the snow cover is quite low. Thereby, the problem of producing the detailed forecast for a certain avalanche path is very actual. In order to get local forecast of the avalanche danger several methods for the description of snow mass are used. Let us consider the most actual among them.

Empirical models are used for the operative analytical presentation of the experimental data without the aim for the study of the process’s mechanism. Mathematical statistics enables to obtain empirical dependences which can be applied for the prediction of the avalanche danger according to the results of processing the hundreds of the document-based cases of the snow avalanching.

Up to the present time, many of the empirical dependences already got a wide approval and they are commonly applied and used in the normative documents. For example, for the determination of the avalanche speed \( v \) because of its run-out it recommended to use formula:

\[
v = \sqrt{\frac{9.8 (\sin \alpha - f \cos \alpha) S}{2}}
\]  

(1)

Where \( \alpha \) is a mean angle of the descent, degrees, \( f \) – is friction coefficient depending on the descent covering \( (0,25 \ldots 0,30) \); \( S \) is the length of descent, m.

A number of empirical dependences are known for describing of the avalanche impact on the obstacle. For example, the power of avalanche influence onto the obstacle \( P_c \), kN, effecting a construction with the height \( h_c \), m, and the width \( b_c \), m, is recommended to determine according to the formula:

\[
P_c = \gamma_s \cdot \frac{v^2 \cdot h_c \cdot b_c}{1.96 \left( 1 - \frac{\gamma_s}{0.917} \right)},
\]

(2)
Where $\gamma_a = 0.05 \ldots 0.45$ – is a mean bulk density of the oncoming snow mass, tons/m$^3$; $v$ is a speed of avalanche, m/s.

Critical depth of snow cover $h_{\text{tmp}}$, m, according to the results of data processing for more than 100 dry snow avalanches in Swiss Alps and Cadastre of avalanches in Russia can be described by the expression [6]

$$h_{\text{tmp}} = 1.83 \cdot \lg 3.36 \cdot h, \quad \text{(3)}$$

Where $h$ – is a mean height of the snow cover at the avalanche-dangerous area, m.

Processing of the data on the catastrophic avalanches in the Kabardino-Balkaria republic for the period from 1970 to 2012 enabled to obtain a number of the empirical formulas for the calculations of the main indexes of the damage effect of avalanche [7]. In particular, the volume of the sliding snow mass can be calculated by the formula:

$$V(\alpha) = (168 \pm 77) + \frac{(1688 \pm 80) - (168 \pm 77)}{\alpha - (30.7 \pm 0.3)} \times \frac{1 + e^{-1}}{1.07 \pm 0.22}, \quad \text{(4)}$$

Where $\alpha$ is measured in degrees, $V$ is measured in thousands of m$^3$.

3. Calculation of avalanche indicators

Empirical models enable not only to calculate certain indexes of the avalanches but also to describe spatial distribution of a snow mass in the avalanche along the mountain descent. For example, in a dependence of the geographical location, parameters of snow and mountain descent snow mass in the process of avalanching can follow not only power-series or log-normal distributions but do that according to gev-distribution (generalized extreme value) or Frechet distribution.

General disadvantages of the empirical models are their averaged and approximate character, an impossibility to reveal the mechanism of the avalanching process and the necessity to have a large amount of the experimental data for the determination of as the form of the analytical expression as of its parameters. Therefore, in spite of the wide distribution, validity and reliability of the empirical models the development of more adequate avalanches models continues; these models take into account physics of the snow mass, geometry of the mountain descent and obstacles allowing more accurate prediction of the avalanche parameters and the indexes of its damage effect.

Just at the first stages of the avalanche scientific study the attempts of model making were undertaken basing on the fundamental physical laws. In the simplest models an avalanche was considered as a whole body in the form of “snow slab” or “snow drop” (figure 1a). And the mass of moving snow was reduced to one point – Mass Point Model) [8].

In the frameworks of these assumptions avalanche motion is typically described by one equation on the basis of a second Newton’s law:

$$M \frac{d^2 x}{dt^2} = Mg \sin \psi - \mu R, \quad \text{(5)}$$

where $M$ – is a mass of the moving snow bulk; $x$ – is a coordinate along a descent; $g$ – is acceleration of gravity; $\psi$ – is a descent angle; $R = Mg \cos \psi$ – is a normal reaction force of a descent. In this form of the equation of motion snow mass moves with a uniform acceleration (figure 1, b).

In spite of the appeared possibility to consider the physics of avalanche model a serious drawback of this class of models is a representation of a snow mass as an integrated solid. In real life, in a number of cases snow mass holds its connectivity only at the first stages of the avalanche motion (no more than 1 second); after that a considerable fragmentation of snow mass occurs and the motion of separate fragments. As a result, physics of motion for the snow fragments changes fundamentally. Avalanche motion resembles the flow of fluid and the use of mass point approximation can result in the simulation
errors of about 50 ... 500 %. Therefore, the development of more adequate models accounting in a more complete manner the physics of avalanching yet remains actual problem.

Models on the basis of mechanics of mass point proved to be most appropriate for the description of snow cover retention at the descent and assessment of the factors which influence on the fracture of a snow cover [9]. This class of models is also widely applied for the assessment of the avalanche impact on the objects of infrastructure and even on the mobile objects [10].

Aggregation of geo-informational systems (GIS) with the models of avalanching considerably facilitates and accelerates solving of a number of problems in the avalanche science [10, 11]. Monte-Carlo method is the numerical technique based on obtaining of a great number of realizations for the random process. As concerning the simulation of avalanches, Monte-Carlo technique is employed for the multiple numerical simulation of avalanching with the random values of coefficients or initial conditions and the following statistical processing of results [10].

A serious problem in simulation of the snow avalanches is in the fact that parameters of the models and input data are determined with rather low accuracy. For example, many coefficients in the model of avalanche can considerably depend on the weather conditions and prehistory of accumulation of snow cover and they cannot be directly measured at the moment of time when it is necessary to perform simulation. However, the intervals in the changes of parameters are known as well as the approximate statistical law. This situation is typical under description of a wide class of the natural processes and objects. In this case it seems reasonable to consider parameters of the models and input data random functions while the mathematical deterministic model (for example, hydrodynamic one) as some operator. Then the output characteristics of the model will be the random ones, and the model itself gets probabilistic meaning [13].

One of the most common GIS for the simulation of snow avalanches is a computer program RAMMS (abbreviation of «rapid mass movements»), developed by the Swiss Institute of snow and avalanches with the participation of Swiss Federal Institute of woods, snow and landscape researches (WSL Institute for Snow and Avalanche Research SLF) [14]. The program is based on a numerical solution of the second order dynamics equation. For the on-screen displaying of the moving avalanche pattern on the monitor of computer the averaging over the depth of a snow stream is utilized. The height and speed of motion for the snow stream are calculated on the preliminary specified digital 3D-models of terrain. In the process of the program use important review information is displayed.

Within the frameworks of this model two types of resistance forces to the motion of the snow flux are considered: the force of a dry Coulomb friction with a coefficient \( \mu \), and also the force proportional to the square of speed of the moving snow mass with a coefficient \( \xi \). Friction resistance in this case is expressed as [14]:

\[
R = \mu N \cos \psi + N \sin \psi,
\]

where \( R \) is the friction force, \( \mu \) is the coefficient of friction, \( N \) is the normal force, \( \cos \psi \) and \( \sin \psi \) are the components of the normal force in the direction of the slope.

\[
F = \xi V^2,
\]

where \( F \) is the force proportional to the square of speed, \( \xi \) is the coefficient, \( V \) is the speed of the moving snow mass.
\[ S = \mu \rho H \rho g \cos \varphi + \frac{\rho g U^2}{\xi} \quad (6) \]

Where \( \rho \) – is a density of snow stream; \( g \) – is acceleration of gravity; \( \varphi \) – is a mean angle of descent in the given point; \( H \) – is the height of stream; \( U \) – is the speed of stream.

In order to determine coefficients of the models and to check its validity the authors used statistical data about avalanches in the area of Valle-de-la-Sionne (from 1999 to 2005). The most serious adequacy of the model seen under description of the motion of very large snow avalanches consisting of the dry snow. At the same time, RAMMS is ineffective when describing humid avalanches and low-capacity avalanches. The authors assume that low-capacity avalanches can simulated by increasing of the values of the coefficients \( \mu \) and \( \xi \), but at first, the preliminary adjustment of the model is required. An additional drawback of the model is that it does not describe snow motion behind the avalanche front edge, in the region of small moving snow masses and the large resistance coefficients. Even less accuracy RAMMS demonstrates when simulating mud flows since they are multi-component systems (fluid, mud, stones, branches, etc.).

4. Improving the adequacy of modeling
In order to increase adequacy of simulation the authors of RAMMS suggested including the granulated snow mass with a fluctuating energy over the granules into the model. According to the authors estimation such modification of the model enables to work with a variable density of snow mass and to predict more accurately the damaging factors of the avalanche.

At present, method of the particles dynamics is most physically adequate while simulating complex environment. Avalanche-forming snow mass is just related to this kind of environment [15-20]. This method consists in the representation of environment by the totality of the interacting particles (material points) implying that their motion in space is described by the laws of classical mechanics. The proposed method is a particular case of the finite element method (FEM) and it is directed at the use of high-performance computational technique. With an increase of the environment discretization meaning an increase in the number of particles the physical adequacy and accuracy of simulation is enhanced. The method is maximum understandable from the physical point of view: in the utmost discretization the environment can be represented as a totality of the interacting atoms. The motion of particles is described by the following equations:

\[ m_k \frac{d^2 \vec{r}_k}{dt^2} = \sum_{n=1}^{N} \Phi(\vec{r}_{kn}, \vec{v}_{kn})\vec{r}_{kn} + \sum_{n=1}^{N} \Psi(\vec{r}_{kn}, \vec{v}_{kn})\vec{v}_{kn} + \vec{\phi}(\vec{r}_k) + \vec{\psi}(\vec{r}_k, \vec{v}_k), \quad (7) \]

where \( m_k \) – is a mass of \( k \)-th particle; \( \vec{r}_k \) and \( \vec{v}_k \) – vectors of position and velocity of the particle

\[ \vec{r}_{kn} = \vec{r}_k - \vec{r}_n, \quad \vec{v}_{kn} = \vec{v}_k - \vec{v}_n, \quad (8) \]

and functions \( \Phi \) and \( \Psi \) describe conservative and non-conservative components of the interaction between the particles; functions \( \phi \) and \( \psi \) describe external conservative and non-conservative force fields. In these equations only pair-wise interaction is concerned but in a number of the problems ternary interactions are also considered, for example, when simulating the flexible shells.

Simulation by particles dynamics technique from the mathematical point of view represents solutions of Cauchy problem for equations (8). Initial conditions include coordinates and velocities for each of the particle. For the numerical integration of the equations describing motion of the particles Runge-Kutta technique, or Verle, Vinyard, Nordzic methods can be used, in a dependence on the right part of equation (7) and the available computational facilities. In order to accelerate calculations a method of the preliminary partitioning of the particles over the cells in a cubic mesh is applied. Method of the particles dynamics assumes almost complete paralleling thus allowing an efficient application of this method at the multi-processor calculation systems.
At the same time majority of the published results on the simulation of avalanches and other similar environments by the particles dynamics technique are too simplified and they are not connected with the real avalanches. To increase adequacy of the models of a certain class it is necessary to realize to the terrain relief, the account of a great number of parameters of snow mass, weather conditions in prehistory of snow accumulation, model verification not with the use of laboratory experiments but with the use of data concerning real avalanches. Moreover, as a rule, usually either avalanching is studied or, as in the example, presented below, an impact of avalanche on the immovable indestructible object with a simplest geometrical shape is explored. Much more practical validity represents the models of the avalanches impact on the objects involved into the motion or damaged under the effect of avalanche.

Thus, particles dynamics method seems to be the most physically adequate for the simulation of avalanches. Currently, the data of the model are actively developed and they become more complicated by different research teams. A new model of motion and interaction with different obstacles for the avalanche-dangerous snow mass is proposed in the work based on the particles dynamics technique.

A mass of snow deposited on a descent of the mountain is represented in the model as a totality of a large number of the separate round elements. Simulation is performed in two-dimensional space $X-Z$, so that axis $X$ is situated in horizontal direction along the quickest descent, while $Z$-axis is directed vertically. Exclusion of a third dimension enables to increase the linear dimensions of the simulated system in the directions $X$ and $Z$ at the given number of the elements (we used up to 100000 elements). The excluded $Y$-axis would be directed along the horizontal direction along a descent plane. Therefore, no any significant phenomena with a snow mass would proceed along this axis, and from this point of view exclusion of $Z$ axis seems quite reasonable, as well.

The state of each element of snow $i$ is determined by four variables: Cartesian coordinates of its center ($x_i, z_i$) and two components of velocity ($v_{xi}, v_{zi}$).

Interaction of the elements in a snow mass between each other as well as with a descent and an obstacle is considered as viscous-elastic one. And a certain element $i$ is subjected to a force impact from each of the surrounding elements $j$:

$$F_i = \sum_{j=1}^{N_E} (F^y_{ij} + F^h_{ij}),$$  \hspace{1cm} (9)

Where $F^y_{ij}$ and $F^h_{ij}$ are the forces of elastic and viscous interaction of the snow elements $i$ and $j$; $N_E$ – is the total number of snow elements in the model.

Elastic forces between the elements appear in a dependence on the distance between their centers $S_i(x_i, z_i)$ and $S_j(x_j, z_j)$, determined by the formula:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (z_i - z_j)^2}.$$  \hspace{1cm} (10)

If the elements of snow mass are tightly bound to each other that is quite possible under certain weather conditions such as slush or ice, then these elements called connected. If the connected elements in the model moved off from each other up to a certain utmost distance, then a restoring force acts between them. Physical interpretation of this fact lies in appearance of the stress under breakout of snow slabs from each other.

In a dependence of the fact if the elements are connected or not connected between themselves, as well as if they are strongly or weakly connected different formulas are used in order to calculate the force:

1) If the elements $i$ and $j$ are not connected, then

$$F^y_{xij} = \begin{cases} c_O(d_{xj} - r_{ij})(x_i - x_j) / r_{ij}, & \text{if } r_{ij} < d_{xj}; \\ 0, & \text{if } r_{ij} \geq d_{xj}; \end{cases}$$  \hspace{1cm} (11)
2) If the elements \( i \) and \( j \) are connected and weakly interact, then

\[
F^Y_{xij} = \begin{cases} 
 c_O (d_\Theta - r_{ij}^2) / r_{ij}, & \text{if } r_{ij} < d_\Theta + d_O; \\
0, & \text{if } r_{ij} \geq d_\Theta + d_O.
\end{cases}
\]

\[
F^Y_{zij} = \begin{cases} 
 c_O (d_\Theta - r_{ij}^2) (z_i - z_j) / r_{ij}, & \text{if } r_{ij} < d_\Theta + d_O; \\
0, & \text{if } r_{ij} \geq d_\Theta + d_O.
\end{cases}
\]

(12)

3) If the elements \( i \) and \( j \) are connected and strongly interact between themselves, then

\[
F^Y_{xij} = \begin{cases} 
 c_C (d_\Theta - r_{ij}^2) (x_i - x_j) / r_{ij}, & \text{if } r_{ij} < d_\Theta + d_C; \\
0, & \text{if } r_{ij} \geq d_\Theta + d_C.
\end{cases}
\]

\[
F^Y_{zij} = \begin{cases} 
 c_C (d_\Theta - r_{ij}^2) (z_i - z_j) / r_{ij}, & \text{if } r_{ij} < d_\Theta + d_C; \\
0, & \text{if } r_{ij} \geq d_\Theta + d_C.
\end{cases}
\]

(13)

Here \( F^Y_{xij} \) and \( F^Y_{zij} \) are Cartesian components of the force \( F^Y_{ij} \); \( c_O \) and \( c_C \) are stiffness coefficients of elastic interaction between the elements corresponding to the weak and strong interaction of the elements.

To calculate the viscous friction force \( F^B_{ij} \) a direct variation dependence of the viscous force on the speed of and agent moving in the medium as a typical variant of force in mechanics. Note, that here an additional coefficient \( (r_{ij} - (d_\Theta + d_m)) \) is introduced, which characterizes mutual penetration of the snow elements into each other.

\[
F^B_{xij} = k_m (r_{ij} - (d_\Theta + d_m)) (v_{xj} - v_{xi});
\]

\[
F^B_{zij} = k_m (r_{ij} - (d_\Theta + d_m)) (v_{zj} - v_{zi});
\]

(14)

Where \( v_{xi}, v_{zi} \) and \( v_{xj}, v_{zj} \) – are Cartesian components of velocity for \( i \)-th and \( j \)-th elements; \( k_m \) – is damping coefficient.

In making the simulation, it is required to follow the evolution of snow mass and determine the integrated impact of snow elements onto the obstacle. To do this one must calculate the trajectory of each elements of snow. Trajectories of the elements are determined based on a solution for the system of equations describing the motion of separate elements that can expressed in accordance with the second Newton’s law:

\[
m_E \frac{d^2 x_i}{dt^2} = \sum_{j=1}^{N_3} (F^Y_{xij} + F^B_{xij}) + c_{E-C} \cdot r_{emi} \cdot s_{xi} + k_v v_{xi};
\]

\[
m_E \frac{d^2 z_i}{dt^2} = \sum_{j=1}^{N_3} (F^Y_{zij} + F^B_{zij}) - m_E g + c_{E-C} \cdot r_{emi} \cdot s_{zi} + k_v v_{zi}.
\]

(15)

Where \( m_E \) – is mass of the snow element.; \( t \) – is time; \( g \) – acceleration gravity; \( c_{E-C} \) and \( k_v \) – coefficients of stiffness and viscosity of viscous-elastic interaction of the \( i \)-th element with a descent surface; \( r_{emi} \) – the distance of mutual incorporation of the \( i \)-th snow element into the surface of a descent; \( s_{xi} \) and \( s_{zi} \) – are Cartesian components of the vector with a unit length, indicating the
direction of the force impact on the \( i \)-th element from the descent; \( v_{xi} \) and \( v_{zi} \) – are Cartesian components of velocity vector for the \( i \)-th element.

System of equations in the form of (15) for all of \( N_E \) elements makes it possible to describe dynamics of snow mass at any moment of time.

5. Conclusions
In the beginning of the simulation experiment, snow elements appear at some height above the descent. Their coordinates specified in a random manner in some limited area. Then, under the impact of the gravity force deposition of the snow elements occurs and formation of the snow cover on a descent. While using the proposed model for prediction of the avalanche danger it is necessary to consider a wide class of physical phenomena such as dynamics of the evolution of snow mass, snow accumulation on the descent surface, as well as just the process of snow avalanching itself. This model takes into account the influence of external factors and impacts on the snow mass, geometry factors of the descents, mechanical motion of separate elements of the snow mass, their plasto-elastic interaction, thermodynamic processes occurring inside the depth of snow mass, resulting in the modification of the properties of the separate snow elements.

For small amounts of snow, it is possible to perform simulation in 3D space \( XYZ \). The state of each element-ball \( E_i \) specified by six variables: Cartesian coordinates of its center \((x_i, y_i, z_i)\) and components of its velocity \((v_{xi}, v_{yi}, v_{zi})\). Mechanical interaction between the elements specified as the elastic-viscous one thus allowing introducing into the model some basic mechanical properties of snow: coefficient of elasticity, coefficient of internal friction, ultimate strain in the tensile test.

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