Information model of the impact of avalanche snow masses on the elements of the landscape infrastructure

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Abstract. The article describes the software implementation of the snow avalanche model based on the modified method of smoothed particles and analyzed the destructive effect of snow mass on infrastructure objects. In this model, the building is considered as a single, non-deformable object, capable of moving in space under the influence of a snow avalanche. The two-dimensional version of the model quite adequately describes the displacement of the building down the slope and overturning relative to one of the edges of the building in the form of a parallelepiped. The model was verified on real data. The model with high adequacy reproduces the real situation at a qualitative level, and with an error of about 4% on a quantitative level. The developed model can be used to predict the characteristics of avalanche damage to buildings in potentially hazardous areas.

1. Introduction
One of the main seasonal risks of natural danger is the spontaneous descent of avalanches. In spite of the fact that avalanche areas occupy 6% of the space of sushi, the problem of a research of the similar phenomena is represented important for timely holding antiavalanche actions. In a zone of transit of avalanches there are settlements, transport communications, communication lines and electricity transmissions, oil and gas pipelines, tourist hotels, etc. More often than others also the railroads, destruction and which blockages lead to long breaks in the movement suffer from avalanches automobile. Within this work obstacles in the form of vehicles and also buildings and constructions are considered. Detailed pilot studies of how obstacles of this or that type, a form and physical characteristics interact with an avalanche, are strongly complicated. Avalanches happen unexpectedly, process of interaction with an obstacle is swift-flowing, it is difficult to record impact of snow weight on an obstacle and to measure quantitatively. Therefore, use in studying of interaction of an avalanche with obstacles of imitating computer modeling is very relevant [1–4].

2. Principles of creation of model
At computer modeling of the movement of avalanche snow masses and consequences of an avalanche it is necessary to consider a wide class of the physical phenomena, such as dynamics of evolution of snow weight, accumulation of snow on a slope and also directly process of a descent of an avalanche [5, 6]. The offered model considers influence of external factors and impacts on snow weight, geometry of slopes, mechanical motion of separate elements of snow weight, their elastoplastic interaction, the thermodynamic processes proceeding in the thickness of snow weight, leading to modification of properties of separate elements of snow.
The snow mass which is depositing on a slope in model is represented as a set of a large number of separate round elements [7-10]. Simulation is made in two-dimensional space X–Z, at the same time the x-axis is located in the horizontal direction along the fastest descent of a slope, and axis Z – in the vertical direction. The exception of the third measurement allows to increase in case of the given number of elements (in calculations used up to 50000 elements) the linear sizes of the modelled system in X directions and Z. The excluded axis Y is located horizontally along the slope plane and therefore practically no significant phenomena with snow mass practically would occur along it - from this point of view, the exclusion of the Y axis is justified. The excluded y axis would be located in the horizontal direction along the slope plane and therefore along it practically there would be no significant phenomena to snow mass – from this point of view the axis Z exception also is reasonable. The status of each element of snow of i is defined by four variables: Cartesian coordinates of its center \((x_i, z_i)\) and two components of speed \((v_{ix}, v_{iz})\). Interaction of elements of snow mass among themselves and also with a slope and a hindrance, is considered viscoelastic.

During modeling it is necessary to track evolution of snow weight and to define total impact of elements of snow on an obstacle. For this purpose, it is necessary to calculate a trajectory of each of snow elements. Trajectories of elements are defined on the basis of the solution of system of the equations of the movement of separate elements which can be written down according to the second law of Newton. [12]. The set of the equations for all elements also describes evolution of snow weight eventually [13-14].

In this model the building is considered as the uniform not deformable object capable to move in space under the influence of an avalanche. The two-dimensional option of model quite adequately describes building shift downhill and capsizing is relative one of building edges in the form of a parallelepiped. The form and the sizes of the building can be changed that allows to check influence of geometrical parameters of a structure on sizes of shift and capsizing of the building in model. For unification of approach to modeling of impact of avalanches on various objects in this model it is supposed that the easy structure is based upon the column base. Setting various breaking points and friction force in fixing points, it is possible to reproduce in model different types of the movement under the influence of an avalanche, for example, only capsizing without shift (at big coefficient of friction) or only shift without capsizing (at small coefficient of friction). The algorithm of calculation of the destroying impact from set of elements of snow on an easy structure is presented in the figure 1. On the basis of this algorithm the computer program "The Program for Modelling of Shift and Capsizing of the Building under the influence of an Avalanche" (the certificate on the state registration of the computer program No. 2016661871 of October 24, 2016) is developed for performance of calculations, necessary for model, and a research of model. The program allows to set key parameters of the building, snow weight, a relief of a slope and to calculate indicators of shift and capsizing of the building, and power impact on the building. As a relief of a surface as well as in the previous model, the rectilinear slope with an embankment on which the building is located is chosen.[8, 15].
3. Experimental use of model
The computer experiment on impact of an avalanche on the building was made as follows. In initial time point the building was placed on an embankment of the set height, and has been strongly connected with a basic surface. At the same time snow weight in initial points was placed at the set height on a slope in the form of rectangular layer $0.6$ m thick and $100$ m long. During the computer experiment snow weight began to move on a slope and at a given time the front of an avalanche reached the building.

Further theoretical research is based on several series of computer experiments. Of the numerous parameters of the avalanche-forming snow mass, one of the most important parameters is chosen: the initial thickness of the snow cover $h_c$. Key parameter of a land relief is the slope corner $\alpha$ [16-18]. The following is chosen from the parameters characterizing the building for a research: height of an embankment at which the building, over $h_{of}$ slope is located; mass of the building of $m_z$; effective coefficient of friction of the building about a surface $k_{ef}$, indirectly characterizing durability of the base of the building. Among indicators of the striking action of an avalanche on the building the following is analyzed further: dependence on time of shift of the center of gravity of the building in the horizontal direction from initial situation under the influence of an avalanche of $L_{cm}(t)$; dependence on building tilt angle time $\phi_{z}(t)$; the maximum shift of the building in the horizontal $L_{cm,max}$ direction. m; maximum tilt angle of the building.
\( \varphi_{n,m} \): the maximum force operating on the building in the horizontal \( F_{bok} \) direction; the maximum pressure on a half-height of a wall of the building of \( P_{0.5} \). In this parameter it is possible to judge whether the avalanche will cause destruction of windows, doors, a breach of walls. Thus, the further research of model consists in change of parameters of snow weight, a land relief, the building and definition of their influence on indicators of the striking avalanche action.

4. Influence of initial thickness of snow cover

Thickness of \( h_{sn} \) of avalanche snow cover significantly influences destructive ability of an avalanche, defines intensity of influence of snow weight and total amount of snow weight. For studying of influence of \( h_{sn} \) on the nature of change of a condition of the building a series of computer experiments in which \( h_{sn} \) changed from 0,25 to 1,00 m with a step of 0,25 m is conducted. For the building parameters of the most typical mountain tourist lodge have been chosen. To a certain thickness of snow cover (about 0,4 m) action of an avalanche doesn’t lead to the shift or capsizing of the building (figures 2, a, b). At this \( L_{sm,m} = 0 \) m and doesn’t exceed a tilt angle of the building 1-2° and causes only insignificant deformations of the building, but without having dug out from the base.

![Graphs](https://via.placeholder.com/150)

**Figure 2.** Influence of thickness of snow cover of \( h_{sn} \) on the size of horizontal shift \( L_{sm,m} \) of the building (a); corner \( \varphi_{n,m} \) of the maximum inclination of the building(b); the maximum horizontal force of \( F_{bok} \) operating on the building (c)

However, at the same time damage of windows and doors of the building because of \( h_{sn} \) of pressure \( P_{0.5} \) upon the building wall, next to an avalanche growing with increase is possible (the figure 2, d).

At increase in thickness of snow cover from 0,5 to 0,6 m there is a failure of the building from the base, but \( L_{sm,m} \) has the insignificant size of 0,1-0,7 m, and the tilt angle of the building is also small (less than
3-4°). Initial thickness of snow cover from 0.60 to 0.85 m causes not only a separation of the building from the base, but also his shift on considerable distance from 0.7 to 3.0 m that taking into account an inclined land relief can cause further falling of the building downhill. At the same time the building can bend on 3-25°, but not overturn. At a descent of the avalanche formed by snow cover with the big initial thickness (more than 0.85 m), action of an avalanche leads not only to the shift, but also capsizing of the building: the maximum tilt angle of the building makes not less than 25-90° (the figure 2, b).

Thus, depending on thickness of avalanche snow cover five options of consequences of impact of an avalanche on the building can be implemented:

- the weak action of an avalanche which isn't causing damages of windows and doors, falling asleep of the building by snow;
- damage of windows and doors without shift and capsizing of the building;
- failure of the building from the base without essential shift;
- essential shift of the building without capsizing;
- essential shift of the building with capsizing.

The dangerous thickness of snow cover leading to the shift or capsizing of the building is more than 0.6 m.

5. Influence of a corner of a slope of the mountain

The slope corner at the same thickness of snow cover (0.6 m) defines a possibility of dispersal of an avalanche and respectively speed and kinetic energy of snow weight at contact with the building. For studying of influence of a corner of a slope α series of computer experiments within which α changed from 15 to 50° at a slow pace 5° (figure 3) is conducted.

![Graphs showing influence of a corner of a slope](image)

**Figure 3.** Influence of a corner of a slope α at a size of horizontal shift $L_{\text{sm, m}}$ of the building (a); corner $\varphi_{\text{n,m}}$ of the maximum inclination of the building (b); the maximum horizontal force of $F_{\text{bok}}$ operating on the building (c)
To increase $\alpha$ naturally there is an increase in size of shift of the building of $L_{\text{shift}}$ (figure 3, a) and $\varphi_{n,m}$ (figure 3, b). A building separation from the base, judging by the site of initial growth of the schedule of $L_{\text{shift}}$ ($\alpha$), begins with corners of a slope 20-25°. At a thickness of snow cover of 0,6 m even at big coal of a slope 50° there is no capsizing of the building: $\varphi_{n,m}$ doesn't exceed 5°. Apparently, in this option of model with increase in a corner of a slope the avalanche loses energy in the hollow between a slope and the building more and more considerably. Therefore, since a corner 35° increase $\alpha$ practically doesn't lead to growth of side force (the figure 3, c) and pressure (the figure 3, d). Therefore, deepening between a slope and the building with a characteristic size about 3 m leads to essential dispersion of energy of an avalanche and reduction of impact on the building.

Thus, increase in a corner of a slope leads to increase in size of shift of the building, a corner of the maximum inclination. However, if the building is raised over a slope, even at big corners of a slope kinetic energy of an avalanche is extinguished in deepening before the building and the building can be displaced only slightly, but not overturn.

Essential shift of buildings can occur at all considered slope corners if thickness of snow cover exceeds size from 0,5 m (for big corners of a slope about 50°) up to 0,7 m (for small corners of a slope about 20°). The safest option of impact on the building – without separation from the base – is implemented in case of slope corners less than 30-35° and thickness of snow cover less than 0,45-0,55 m.

6. Influence of height of raising of the building over a slope
It has been established above that the hollow between a slope and the building can significantly weaken an avalanche. For more detailed studying of this effect a series of computer experiments in which building raising height over a slope of $h_{zd}$ changed from -1,0 to 3,0 m with a step 0,5 m (figure 4) is conducted. The $h_{zd}$ parameter was set so that at zero $h_{zd}$ value the slope passed into the flat platform without deepening. At negative $h_{zd}$ values the building hasn't been lifted over a slope, and on the contrary, located in deepening of a slope.

It is revealed that the relief form before the building significantly influences indicators of the striking avalanche action. So, at a thickness of snow cover of 0,6 m and coal of a slope 30° there was a guaranteed capsizing the building at all $h_{zd}$ values less or equal 1 m (figures 4, a, b). However already since $h_{zd} = 2$ m avalanche action practically doesn't cause the shift of the building and its essential inclination. Such essential dependence of the striking action on a form of deepening or a ledge of a relief before the building can be explained as follows. The greatest striking impact is made by the lower part of an avalanche up to 0,6...1,2 m high. If the building is located on an embankment, the lower part of an avalanche influences an embankment and the main part of energy of an avalanche dissipates in deepening before the building. However, if before the building there is no deepening or even the building "is drowned" in a slope, the lower part of an avalanche makes impact directly on the building that leads to much more expressed shift and a tilt angle.

Thus, it is expedient to place buildings on hillsides so that between the building and a slope there was a deepening not less than 3 m in depth in which the main part of energy of an avalanche will dissipate. The high danger is constituted by placement of buildings in deepening of a relief as the avalanche layer having the greatest energy will directly influence the building.
Figure 4. Influence of height of raising of the building of $h_{zd}$ over a slope at a size of horizontal shift $L_{sm,m}$ of the building (a); corner $\varphi_{n,m}$ of the maximum inclination of the building(b); maximum horizontal force of $F_{bok}$ (c)

7. Confirmation of adequacy of model with use of real data on damages of buildings by avalanches

Detailed documents on an avalanche, background, land relief and on the damages put with an avalanche are necessary for verification of the developed model. Some avalanches cause a serious public response therefore are carefully documented and lit in media and scientific works. An inspection of adequacy of model is carried out on the basis of the most complete set of data which is in open access: about the avalanche which has descended to Longyearbyen on December 20, 2015 in 22 h [17].

Norwegian city of Longyear byen (English Longyear, Norwegian Longyearbyen), located on Svalbard archipelago, represents the important tourist center as the city is considered the most northern city in the world, with the operating airport, the university and the population more than 2 thousand people. The avalanche which has descended from Mount Sukkertoppen as a result of a whole gale and snowfall has damaged 11 houses and has led to death of two people. Damage were sustained by the same two-storeyed wooden houses, and the snow stream has shifted some of them from the bases and has dragged tens of meters, the part of houses was inclined, and some economic constructions are overturned. An incident in Longyearbyen has received extended coverage in media, the numerous schemes explaining features of an avalanche, satellite photos, photos from the helicopter directly after an avalanche, the photo from the place of emergency situation have been published (figure 5).

Collected documents allow to determine geometrical parameters, necessary for the developed model, to reproduce the corresponding avalanche in model and to check her action for the corresponding models of buildings. Features of a structure of buildings and their arrangement ranks parallel to the front of an avalanche allows to transfer with high precision them to models and to make verification of model.

According to photos and the physical map (figure 5) it has been established that the surface relief near the modelled houses can be presented with high precision in the form of the broken line consisting of two
pieces: the inclined site (a mountain slope) and the horizontal site on which has to occur avalanches and on which the house has to move.

Geometrical parameters of the site of a slope on which the snow layer which has created an avalanche settled down have been determined by isolines of the physical map: the rupture of layer has come at the height of 60 ± 3 m from a horizontal surface, and at distance 165 ± 5 m from the beginning of a slope, at the same time the corner of a slope has made 19,9°. On slopes with such small tilt angle 15...25° considerable volumes of snow collect, and avalanches from such slopes can cause catastrophic consequences [20, 21]. The next row (houses No. 30, 32, 34, 36) about 10 m from the beginning of a slope are located at LZ-S distance. The overall dimensions of the house measured according to satellite photos and photos from a surface were equal (10,0 ± 0,5) x (7,6 ± 0,4) m². Thickness of snow cover was accepted 1,0 m that is typical value for slopes of Spitsbergen in December.

![Figure 5](image_url)

**Figure 5.** An arrangement of buildings till the avalanche (a, the satellite photo) and damages after an avalanche (b, the photo from the helicopter) [19]

Geometrical parameters of a land relief and the house have been transferred to model. The first computer experiments have led to the shift and an inclination of the house similar which were really occurring (figure 6). On an available photo and video content the card of shift and turn of ten houses under the influence of an avalanche is restored. At recovery of the scheme of shift and turn of houses besides the photo the figure 5, available photos on the Internet from four other foreshortenings, a video from the quadcopter which has flown around a destruction zone in several hours after an avalanche and also the numerous pictures taken about the surfaces allowing to establish the nature of contact of houses were used. The restoration error by this method of coordinates of houses after shift doesn’t exceed 1,0...1,5 m, angular position of houses – 3...4°. For each displaced house the shift distance has been defined.
Figure 6. The scheme of shifts and turns of houses under the influence of an avalanche

In model action of an avalanche on six houses (№16, 18, 22, 30, 32, 34) which at shift an avalanche or didn't concern other houses, or concerned only in a final point of a trajectory is reproduced. For each explored house entry conditions for modeling varied a little: house distance to a slope, thickness of snow cover in this vertical section and information on a house emphasis to other house in a final point of a trajectory (Table 1). Thickness of snow cover for the houses 30, 32, 34 which have directly apprehended the front of an avalanche is accepted equal 1,0 m. For the house 22 which was shielded by houses 30 and 32 thickness of 0,7 m is accepted. Houses 18 and 16 were located on avalanche border therefore haven't undergone serious shifts, and for them thickness of snow cover of 0,8 and 0,6 m respectively is accepted.

Table 1. Entry conditions for modeling

| house number | Distance from the house to a slope L3-C, m | Thickness of snow cover h_{sa}, m | Distance shift against the stop L_{sm}, m |
|--------------|-----------------------------------------|---------------------------------|-----------------|
| 16           | 46.8                                    | 0.6                             | –               |
| 18           | 48.0                                    | 0.8                             | –               |
| 22           | 50.4                                    | 0.7                             | –               |
Because of difference of entry conditions of the house in model were displaced and bent variously, considerably corresponding to the real card of shifts of houses.

For each of six houses the separate computer experiment for definition of indicators of the striking avalanche action was made. For houses 30, 32, 34 with which the avalanche interacted first of all the greatest power impact was made not at once: at first the front of an avalanche has broken houses from piles and has rather slowly moved on 17...27 m, and only after that the main snow weight has rendered the largest force on houses, and having reported to houses big acceleration. The kinetic energy reserved by houses 30, 32, 34 and further pressure of an avalanche has caused considerable further movement of houses. The houses located in the second row from a slope have received the greatest power influence. For houses 30, 32, 34 and further pressure of an avalanche has caused considerable further movement of houses 30, 32, 34 and further pressure of an avalanche has caused considerable further movement of houses of the first row, according to the shift of houses have occurred also on smaller distances. During modeling dependences of distance of shift on time of $L_{sm}(t)$ and a tilt angle on time $\varphi_n(t)$ are received (figure 7).

![Figure 7. Dependence on time of $t$ of size of shift of $L_{sm}$ (a) and tilt angle $\varphi_n$ (b) houses](image)

By dependences of $L_{sm}(t)$ it has been determined that about 2/3 distances from the full size of shift of the house moved with a constant speed then on 1/3 the remained distances impact of an avalanche gradually decreased and the speed of the house gradually faded (the figure 9, a).

Under the influence of an avalanche the tilt angle of each modelled house changed under the difficult law (there was an inclination and jolting of the house), at the same time for houses 30, 32, 34 the inclination gradually decreased and the speed of the house gradually faded (the figure 9, b). By the time of contact with second of houses the avalanche was near already a little weakened therefore accelerations of houses 16, 18, 22 were lower, than houses of the first row, according to the shift of houses have occurred also on smaller distances. During modeling dependences of distance of shift on time of $L_{sm}(t)$ and a tilt angle on time $\varphi_n(t)$ are received (figure 7).

![Figure 7. Dependence on time of $t$ of size of shift of $L_{sm}$ (a) and tilt angle $\varphi_n$ (b) houses](image)

Comparison of shifts of six modelled houses to the real card of shifts allows to claim that the model is adequate to real data (table 2). (Note: the – symbol has noted cases in which it is impossible to compare model data with real because the real inclination of buildings has happened because of their hit of deepening of a relief while in model the surface of the movement of buildings was equal). The average error of definition of 10 indicators of shift and an inclination has made 4.3%.

It is necessary to emphasize that the parameter of thickness of snow cover was appointed to each of the modelled houses, proceeding from his arrangement in relation to a slope and edge of an avalanche. And such approach has allowed to receive shifts of houses very close to real.

### Table 2. Shifts and tilt angles of buildings under the influence of an avalanche

| Number of the building | Shift $L_{sm,m}$ | Slope angle, $\varphi_n$, degree |
|------------------------|------------------|---------------------------------|
|                        | real | in model | distinction | real | in model | distinction |

|                | 30   | 10,0     | 1,0       | 79,0  |
|----------------|------|----------|-----------|-------|
|                | 32   | 11,3     | 1,0       | –     |
|                | 34   | 12,1     | 1,0       | 38,9  |
Thus, the developed model has allowed not only to reproduce the shifts of houses close to real, but also to restore a detailed picture of mechanical behavior of houses under the influence of an avalanche. The developed model calibrated on an avalanche to Longyearbyen can be used for forecasting of the striking action of the following avalanches for other houses of this city. The same way the developed model can be used for forecasting of avalanche damages of buildings to other potentially dangerous zones.

8. Conclusion

The avalanche model on the basis of the modified method of smoothed particles is presented in article and the analysis of destructive impact of snow weight on infrastructure facilities is carried out. In this model the building is considered as the uniform not deformable object capable to move in space under the influence of an avalanche. The two-dimensional option of model quite adequately describes building shift downhill and capsizing is relative one of building edges in the form of a parallelepiped. The form and the sizes of the building can be changed that allows to check influence of geometrical parameters of a structure on sizes of shift and capsizing of the building in model. For unification of approach to modeling of impact of avalanches on various objects in this model it is supposed that an easy structural shift and capsizing of the building in model. For unification of approach to modeling of impact of avalanches on various objects in this model it is supposed that the easy structure is based upon the column base. Setting various breaking points and friction force in fixing points, it is possible to reproduce in model different types of the movement under the influence of an avalanche, for example, only capsizing without shift (at big coefficient of friction) or only shift without capsizing (at small coefficient of friction).

Verification of model on the basis of the most complete set of data on the avalanche which has descended to Longyearbyen on December 20, 2015 in 22 h Model with high adequacy is carried out reproduces a real situation at the qualitative level, and with a margin error about 4% at the quantitative level. Thus, the developed model can be used for forecasting of characteristics of avalanche damages of buildings to other potentially dangerous zones.

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