Requirements for the avalanche protection catching and deflecting dams design in Russia and the European Union

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Abstract. The requirements for the avalanche structures (catching and deflecting dams) design used in the Russian Federation are considered in the article. The comparative analysis with similar requirements in the European Union is conducted.

Introduction
Snow avalanches are a widespread natural phenomenon significantly complicating the mountain territories economic development and possessing a threat to human life [1]. To protect the buildings from avalanches, various methods have been developed, including organizational and preventive measures, as well as the construction of anti-avalanche protective structures [2]. In this article the requirements for the design of avalanche structures (catching and deflecting dams) used in Russia and conducted some comparative analysis with similar requirements in the European Union are considered.

For the anti-avalanche structures design, both in terms of design solutions and materials, it is necessary to adopt the most rational means and adapt them to the structures’ specific conditions. The greatest difficulties in carrying out calculations of structures that ensure the safety of structures are: the choice of the main system or the design scheme of the object and the assessment of loads affecting the system. The physical processes modeling occurring in avalanches depending on their types and many other factors affecting the dynamics of processes is a significant difficulty. Power loads arising from the avalanches’ movement should be safely perceived by the appropriate anti-avalanche structures.

The traditional design principles for avalanche dams
The current instructions basis for the anti-avalanche structures design in Russia and European Union is the avalanche (dense core) movement consideration as a solid body on an inclined surface, for the description of which the point-mass mechanics methods are used [3-7]. The avalanche dam height is determined from the conditions of entire avalanche detention, based on the energy conservation law - the avalanche kinetic energy transition at the time of interaction with the obstacle in the potential energy.

In accordance with the current instructions used in the Russia [8], avalanche structures (dams) should be built in the avalanche deposition place, where avalanche speed is less than 25 m/s. According to the traditional methods used in the European Union design [3] (Johannesson T.
Overview of traditional design principles for avalanche dams, the avalanche dam height \( H_D \) is usually determined from the equation:

\[
H_D = h_u + h_f + h_s
\]  

(1)

where, \( h_u \) - is the height due to the kinetic energy (avalanche velocity) (m); \( h_f \) - is the thickness of the avalanche flowing dense core (m); \( h_s \) - is the thickness of the snow cover and previous avalanche deposits on the ground from the upland dam side (m).

Values of \( h_f \) and \( h_s \) in the Eq.1 usually amount to several meters (in open slopes), and are evaluated on the snow accumulation conditions basis and avalanches’ frequency for a given area. The value of \( h_u \) for catching dams is calculated according to the equation:

\[
h_u = \frac{u^2}{2g\lambda}
\]  

(2)

where, \( u \) - is the avalanche velocity at the dam location chosen in the design (m/c); \( g = 9.8 \text{ m/s}^2 \) is the gravity acceleration, and \( \lambda \) is an empirical parameter intended to reflect the momentum loss when the avalanche hits the dam, as well as the friction effect on the avalanche flow during run-up along the upstream dam.

The \( \lambda \) value for catching dams is usually chosen between 1 and 2 (sometimes higher), with higher values used for dams with steep walls on the side of the avalanche approach. The higher values of \( \lambda \) (corresponding to lower dams) are chosen where the potential for large avalanches is considered rather small, whereas the lower values of \( \lambda \) (higher dams) are chosen for avalanche paths where extreme avalanches where the large volumes may be released.

The artificial excavation capacity in front of the dam should be large enough to accommodate the avalanche estimated volume and the amount of snow accumulated before the avalanche. The capacity depends on the dam upstream slope topography, the slope of avalanche deposits piled up in front of the dam, and the relative snow compaction.

The deflecting dam’s height is calculated by using Equation 1, as in the case of catching dams, and the value of \( h_u \) is determined according to the equation:

\[
h_u = \frac{(u \sin \phi)^2}{2g\lambda}
\]  

(3)

where, \( \phi \) - is the deflection angle of the dam. The values of \( h_f \) and \( h_s \) are defined as for the catching dams. The \( \lambda \) parameter for deflecting dams is usually taken to be 1 - the loss of momentum and friction during the interaction of the avalanche with the dam is not taken into account. This leads to higher projected dam, but is considered as an additional safety measure – there is uncertainty in determining the avalanche deflection angle.

Thus, the traditional principles on the design of avalanche structures (dams) in the Russia and in the European Union have similar design schemes. At the same time, the standards in Russia are more stringent – the construction of dams in the area of avalanche speeds less than 25 m/s (in the European recommendations there are no restrictions on the speed of avalanches).

The avalanche parameters measurements and their impact results on dams showed that avalanches in some cases overcame obstacles, under conditions when theoretically this was not expected [3]. In other cases, observations of the avalanches run-up on protective artificial dams and natural obstacles better agreement with the theory, although for some natural avalanches is difficult to explain [3] (Johannesson T., Hakomardottir K., Harbitz C., Domaas U., Naaim M. Deflecting and catching dams). At the time, this discrepancy is the most important unresolved issue regarding the avalanches’
interaction with dams. It is very difficult to design a protective structure that can stop the powerful avalanches movement. When designing dams, there is always considerable uncertainty associated with the choice of the avalanche velocity calculated values, and in the European recommendations with the choice of the coefficient $\lambda$ in Eq.2. An important issue in relation to the dams’ effectiveness is the extent to which they reduce the avalanches range that are not completely stopped. When revaluing the avalanche danger of the site after the protective structures construction it is necessary to consider the reduction of avalanches run-out. This is of great practical importance for the dams’ design. An avalanche that partially overcomes a protective structure, but which ejection range does not reach the protected object, is relatively harmless. Therefore, under certain circumstances, it may be appropriate to design a dam, partially overflowing with avalanche parameters laid down in the project. However, given the existing understanding of interaction mechanism between the avalanche flow and the obstacle, this approach involves significant risks.

**Improved design criteria for catching and deflecting dams**

The longest (since 1981) avalanche studies have been carried out in the Western Norway [9-13] in the Ryggefonn project, named after the avalanche site. The experiments carried out in conjunction with theoretical studies on numerical modeling of avalanche movement [5] significantly expanded the understanding of the interaction physical process between avalanches and structures. This made it possible to formulate improved design criteria for catching and deflecting dams on the basis of more advanced dynamic concepts, which make it possible to eliminate some inconsistencies associated with traditional design criteria for such structures. The proposed criteria are given in the report of the European Commission [3]. The proposed criteria are based on the avalanche movement mechanism consideration as a continuous fluid flow, subject to the hydraulics laws— the shallow water equation (also called the San-Venant equations, provided that the horizontal scale of the flow is much larger than the vertical one). In fact, it is assumed that the avalanche flow depth is small in comparison with the horizontal spread of the avalanche, which results in averaging the flow parameters in depth. Under the condition of depth averaging, the dense avalanche core is considered as a shallow free surface with a gravitational flow, which can be described by the flow depth $h$ and the depth-averaged velocity $u$. The small gravitational flows dynamics with a free surface is characterized by the Froude number:

$$Fr = \frac{u}{\sqrt{gh \cos \Psi}}$$

(4)

where, $\Psi$ - is the terrain slope; $g$ - is the gravity acceleration. The Froude number is the flow velocity ratio to the velocity of the low-amplitude free surface of the gravitational wave and corresponds to the Mach number in gas flows. The Froude number for the dense core of natural snowdry avalanches is approximately 5 - 10 [13], which means that such avalanches are in the supercritical range of the flow determined by the values $Fr > 1$. The new criteria proposed in the European Union are based on two requirements. First, it is necessary to prevent the flow in the supercritical state through the dam, and secondly, the height of the dam (both deflecting and catching) should be higher than the depth of the flow. It is proposed that the estimated height of both the catching and deflecting dams should be determined on the basis of essentially the same dynamic principles and implemented in stages.

1. The corresponding calculated values for the velocity $u_1$, depth of avalanche flow $h_1$ at the location of the dam and height of snow cover in the area upstream from the dam, $h_5$, are estimated.
2. The deflection angle $\phi$ (for catching dam $\phi = 90^\circ$) is determined for the deflection dam.
3. Froude $Fr$ Number is calculated – Eq.4.
4. The ratio of momentum $k$ is defined:

$$k = 0.75 \quad \text{for} \quad \alpha > 60^\circ, \quad k = 0.75 + 0.1(60^\circ - \alpha)/30^\circ \quad \text{for} \quad 30^\circ \leq \alpha \leq 60^\circ$$

(5)
The coefficient $k$ is introduced to account for momentum loss in the avalanche interaction with an obstacle and depends on the slope angle of dam upland side relative to the relief $\alpha$.

5. The minimum dam height is defined as the sum of the critical dam height $H_{cr}$, and the corresponding critical flow depth $h_{cr}$ (Figure 1).

![Figure 1](image)

Figure 1. $H_{cr}$ - critical height of the dam, $h_{cr}$ - critical flow depth, $h_s$ - is the height of the snow cover in front of the dam, $h_l$ - is the avalanche flow depth in front of the dam [3].

The critical dam height $H_{cr}$ is the height at which the avalanche flow in interaction with the dam passes from the supercritical to the subcritical state. Height $H_{cr}$ is found from the expression:

$$H_{cr} / h_l = \frac{1}{k} + \frac{1}{2}(k \cdot Fr \sin \phi)^2 - \frac{3}{2}(Fr \sin \phi)^{2/3}$$

(6)

The stream depth at $H_{cr}$ is called the critical depth of $h_{cr}$ and is determined by the expression

$$\frac{h_{cr}}{h_l} = (Fr \sin \phi)^{2/3}$$

(7)

The flow passes from the critical state to the subcritical at the height of $H_{cr}$, the depth of the flow is equal to $h_{cr}$, and the flow surface is at the height of $H_{cr} + h_{cr}$ above the snow cover. If the height of the dam is lower than $H_{cr}$, the main core of the avalanche can overflow or “jump” over the dam, and if the height is lower than $H_{cr} + h_{cr}$, the avalanche front can partially overflow the dam. In order to prevent the dam from overflowing, its height above the snow cover should be greater than $H_{cr} + h_{cr}$:

$$\frac{(H_{cr} + h_{cr})}{h_l} = \frac{1}{k} + \frac{1}{2}(k \cdot Fr \sin \phi)^2 - \frac{1}{2}(Fr \sin \phi)^{2/3}$$

(8)

Figure 2 shows the dependences $(H_{cr} + h_{cr})/h_l$ on the Froude number and the deflection angle $\phi$ (for deflecting dams).
Figure 2. Left: Value \((H_{cr} + h_{cr})/h_1\) for the deflecting dam depending on the deflection angle \(\Phi\) and different values of the Froude -Fr number. Right: value \((H_{cr} + h_{cr})/h_1\) for the catching dam as a function of Froude number.

Solid lines show the calculations results according to the new criteria, dotted lines – according to the traditional criteria. The momentum loss in the avalanche interaction with the dam was not taken into account \((k = 1, \lambda = 1)\). The calculations are performed for horizontal terrain \((\Psi = 0)\). It follows from the results that for dams, the proposed criteria give results similar to the traditional method. The calculated values of the deflecting dams heights for the proposed criteria are slightly lower, the difference depends on both the deflection angle \(\Phi\) and the Froude number.

A number of observations of natural avalanches and their impact on artificial defenses, and natural obstacles were used to check the proposed criteria for choosing the height of dams, \([3, 12]\). A large set of data was obtained in Norway, where information on the effects of 15 avalanches was collected and analyzed, together with data on obstacle geometry and mathematical modeling of avalanche movements. Similar data on avalanches in the Iceland and the France were analyzed. A total of 22 cases of avalanches were considered. A detailed results analysis is presented in the report of the European Commission \([3]\). In cases where the depth of the flow and the velocity of the avalanche on the approach to the obstacle were not fixed, these parameters were calculated by numerical modeling (two-dimensional models with averaging parameters on the depth of the avalanche flow were used \([7-9]\)). The vertical avalanches run-up was recorded on the obstacles marks. The results of the analysis showed that the run-up levels of several medium and large avalanches were consistent with the proposed criteria. At the Ryggfonna \([14]\), in some cases, large values of the avalanche flow run-up were observed in comparison with the calculated values. These discrepancies can be explained to some extent by the uncertainty of the data and the calculated values of flow velocity and depth, but this is hardly the only explanation. Some of the marks of run-up can be caused by the effect of the mixed layer or the powder component of the avalanche and be placed above the height reached by the dense core. However, this cannot explain the full overflow of the dam Kisardalur (Iceland), the avalanche completely covered the dam, leaving very few snow deposits with the side of the foot obstacles. Another example is a medium-sized avalanche in Seydisfjordur (Eastern Iceland) in April 2006. The avalanche that came down overflowed the 20-meter dam also, leaving small deposits of snow on the upland side of the dam \([3]\) (Johannesson T., Hakonardottir K., Harbitz C., Domaas U., Naaim M. Deflecting and catching dams). Such facts indicate the imperfection of the proposed criteria, which do not take into account the complexity of the avalanche interaction dynamics with the obstacle. Considerable uncertainty arises when assessing the effectiveness of protective structures under the condition of avalanches complete stopping. If we calculate the required height of the dam, it turns out that the Ryggefonna dam can completely stop avalanches at speeds \(u_1 < 13\) m/s, provided that there is no snow cover and previous avalanche deposits on the upland side of the dam. This example shows that the use of dams as protective measures is limited to the final section of the avalanche release zone or to stopping low-velocity avalanches. This conclusion is clearly inconsistent with the current recommendations for the design of protective dams (both in the Russia and in the European Union) set.
out above and calls into question the effectiveness of dams, in particular their use to stop or reduce the run-out of rapid snow avalanches.

**Summary**

The current instructions for the avalanche dams design in Russia and European Union use similar calculation schemes based on the consideration of the avalanche movement as a solid on an inclined surface. The natural avalanches research and observation results show that in some cases, the avalanche overcame the defenses, at a time when theoretically this is not expected. The improved criteria for calculating the height of protective dams proposed in the European Union are based on a more advanced dynamic concept – the transition of supercritical avalanche flow to the subcritical flow regime. However, the proposed criteria are not fully consistent with observations on the impact of avalanches on dams and natural obstacles. For many avalanches, the run-up is consistent with the calculated data, but in some cases large values of the avalanche flow run-up have been observed. Despite this progress, understanding of the snow avalanches dynamics impact on obstacles remains incomplete, so the formulation of the new criteria is based to some extent on subjective or not well-founded considerations.

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