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DESIGN OF SNOW AVALANCHE DEFLECTING DAMS

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ABSTRACT

Extensive effort has been put into improved understanding of avalanche deflection over the last two years. This paper discusses construction of deflecting dams in steep terrain, and gives an in-depth description of the recent design of two deflecting dams in western Norway. The design is based on a computational/empirical approach convenient for practitioners. Trajectories and preliminary run-up heights on the deflecting dam are first calculated using a centre-of-mass model based on the Voellmy-Perla equation. To compensate for the limitations of a centre-of-mass consideration, the run-up heights are subsequently calibrated utilising observations of six full-scale avalanches in terrain formations acting as "natural deflecting dams".

The functionality of the two dams is demonstrated by comparisons between the design criteria and the observations of four major avalanches impacting the two dams shortly after completion. The validity of the method is further demonstrated by comparison of calculated and observed run-up heights for avalanches impacting the deflection dam in Flateyri, Iceland. The observations on the constructed dams are finally used to update the calibration procedure.

INTRODUCTION

Increased human activity in mountain regions, deforestation from pollution, forestry and ski resorts as well as a general reduced acceptance of risk have caused a growing demand for avalanche protective measures. Over the last few years, such protection is more often obtained by constructing dams that deflect the course of dense snow avalanches. The basic idea is that it is easier to divert the avalanche then to stop it completely.

A better understanding of the behaviour of snow avalanches upon deflecting dams is strongly needed for improved design and cost-benefit evaluations. The obvious way to obtain improved understanding is to collect information on the observed effects of natural deflecting dams. Subsequently it is desirable to simulate the behaviour of snow avalanches on deflecting dams by computational models.

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Harbitz and Domaas (1997, 1999) describe the effects of natural deflecting dams on reported avalanches. The descriptions fulfil the more and more common understanding among avalanche researchers that the full avalanche path including the release zone has to be mapped to provide all the information needed for model verification, etc.

Computational models for design of avalanche protective measures should ideally describe the complex three-dimensional flow of a compressible and cohesive medium around obstacles. Further insight may alternatively be obtained by a large number of experiments. However, this is normally an expensive approach, and the results may be of limited quantitative value for other case studies.

None of the papers dealing theoretically or experimentally explicitly with run-up heights discuss deflection effects (Chu et al 1995, Hungr and McClung 1987, McClung & Mears 1995). Nevertheless, simulations of avalanches on deflecting dams have to take into account that real avalanche flows are three-dimensional.

Computational models for dense snow avalanches in three-dimensional terrain are now being developed in Italy (Nettuno 1996), Switzerland (Gruber et al 1998) and Austria (Sampl and Zwinger 1999). Irgens et al (1998) focus explicitly on dense snow avalanches on deflecting dams. They back calculate historic events and compare results from the Norwegian continuum model for avalanche flow in a three-dimensional terrain (Irgens in prep.), with results from the centre-of-mass model described below.

In spite of the recent progress in the modelling of avalanches, there is still a strong need for improved methods in hazard zoning and design of protective measures. In this paper we present the design process behind two deflecting dams in western Norway. The design is based on a computational/empirical approach convenient for practitioners. Preliminary trajectories and run-up heights on the deflecting dams are first calculated using a centre-of-mass model based on the Voellmy-Perla equation. Subsequently the run-up heights are calibrated utilising observations of six full-scale avalanches in terrain formations acting as "natural deflecting dams" to overcome the shortcomings of a centre-of-mass consideration. The method was first presented by Domaas and Harbitz (1998). For practical use, the method is an alternative to the more complex and partly unverified three-dimensional models listed above.

The functionality of the two dams is demonstrated by comparisons between the design criteria and the observations of four major avalanches impacting the two dams shortly after completion. The validity of the method is further demonstrated by comparison of calculated and observed run-up heights for avalanches impacting the deflection dam in Flateyri, Iceland.

THE FUNDAMENTALS OF AVALANCHE DEFLECTING DAMS

Location and configuration

The optimal deflecting dam is built in steep terrain and adjusts the course of an avalanche without a severe reduction of avalanche velocity and deposition of masses along the dam wall. Hence, the effective height is sustained for subsequent events.

The easiest way to control an avalanche is to guide it along a gently curving channel. However, this often requires a very long dam following a too steep talus. On the upper part of the talus the dam may be wide and the channel too narrow.

Preferably, the talus should be utilised to reduce the dam height provided the channel width is maintained down the talus. Too high dams in steep terrain may in fact originate new release zones along the walls.

The configuration of the terrain upstream of the dam is of great importance for the functionality. The terrain in Vassdalen and Gaukheidalen in Nordland, northern Norway, illustrates this, Fig. 1. In Vassdalen, the contour lines are not curved upstream of the natural deflecting dam, giving a large angle of incidence and a high run-up. In contrast, the upstream contour lines in Gaukheidalen are curved and end up perpendicular to the centre line of the natural deflecting dam. Hence, the effective angle of incidence and the run-up height are reduced because the avalanche is partly deflected before impact. Besides, a larger part of the avalanche is guided away from the dam without climbing it. Irgens et al. (1998) and Harbitz and Domaas (1997, 1999) further describe the avalanches at these locations.

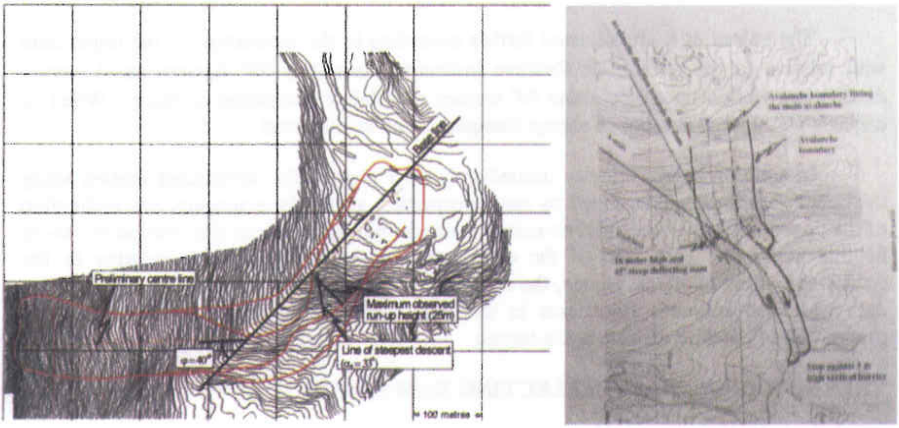

Figure 1: Maps of Vassdalen with 2 m contour line interval (left) and Gaukheidalen with 5 m contour line interval (right). The areas shown correspond to 800x600 m^2 and 625x925m^2, respectively.

Special attention should be paid to the fact that the maximum run-up is reached downstream of the point of attack. With a reliable prediction of the avalanche behaviour along the dam, the dam height can be reduced in the upper and lower sections.

Quantities determining avalanche deflection and run-up

Run-up heights on deflecting dams are traditionally deduced by assuming that all kinetic energy in the avalanche motion perpendicular to the dam is transferred to potential energy when the avalanche climbs the dam. However, this method does not take account of the inclinations of the terrain and the upper dam wall.

As avalanche deflection is a highly complex process, the analyses should rather be divided into three parts: (1) the motion before dam impact; (2) the energy loss and deflection at impact; (3) the motion along the upper dam wall.

The properties and the volume of the flowing snow masses, and the terrain above the dam determine the motion prior to impact. These aspects are more or less reflected by the avalanche velocity immediately before impact.

Energy dissipation and deflection at impact are determined by the coefficient of restitution, k, and the orientation and configuration of the dam relative to the terrain, reflected by the velocity difference before and after impact. It is observed that smooth deflection, gentle dam slope, as well as wet and slow avalanches not being much compressed at impact, favour low energy dissipation, i.e. high values of k and relatively larger run-up heights. Abrupt local deflection and steep dam slopes favour reduced run-up heights, partly due to compression of the snow masses in motion.

In practical applications the value of k is selected in the range 0.0-1.0 based on the expected avalanche dynamics and the impact zone by the dam. For a dry, dense avalanche hitting a traditional dam slope (inclination 1:1.5=34°), significant energy dissipation can be expected at impact. If the angle of incidence is larger than 40°, a preliminary value k=0.0 is applied, i.e. the velocity component normal to the upper dam wall is completely lost at impact. At angles of incidence about 30°, k=0.5 is applied for a medium dissipation of energy. However, if the diversion is less then 20°, less energy loss is expected, i.e. $k \approx 1.0$.

The values of k are adjusted further according to the inclination of the upper dam wall relative to the terrain, ψ. Relative inclination less than 30° favours small energy dissipation, while values of ψ about 40° implies a moderate dissipation of energy. When ψ exceeds 50°, a large amount of energy dissipation can be expected.

In addition to the velocity immediately after impact, the subsequent motion along the upper dam wall is determined by snow properties, avalanche extension, and inclination of the upper dam wall. The chief concern in dam design is the spatial distribution of run-up heights above the base line of the dam, and not the run-up heights relative to the (undefined) point of attack. Hence, the orientation of the base line in the plane of the upper dam wall also becomes significant in this part. This line is again determined by the orientation of the dam relative to the terrain.

THE CENTRE-OF-MASS DEFLECTING DAM MODEL

Governing equations

A centre-of-mass consideration does not include any effects of the avalanche extension on the dynamics. Hence, the model results will be encumbered with obvious restrictions. For this reason, a simplified geometry study is preferred to analyse the influence of avalanche impact velocity, terrain inclination, dam configuration, and dam orientation on avalanche course deflection and run-up along a deflection dam. An additional advantage of a simplified geometry study is that the deflecting dam does not have to be superimposed on a complex digital terrain.

The avalanche velocity immediately before impact, v_T, is found by running the PCM model (Perla et al, 1980). This model for centre-of-mass velocity calculations along the centre-line of a prescribed avalanche path applies the Voellmy-Perla equation that includes a resistance force represented by a dynamic drag and a Coulomb friction. Effects of horizontal curvature are not included. The dry friction coefficient, μ, and the mass-to-drag ratio, M/D, are tuned to obtain the observed run-out distance. However, it is uncertain whether the avalanche would have reached the same run-out distance and velocity profile

without the influence of the deflecting dam, probably causing compression and energy dissipation due to impact. Consequently, one would expect that the real value of v_T is higher than calculated by the PCM model. On the other hand, experience has revealed that the PCM model often overestimates the velocities in the avalanche track. In any case, the tuned values of μ and M/D are subsequently applied in the deflecting dam model.

The deflecting dam model for avalanche motion along the upper wall of a retaining dam is another centre-of-mass model based on the Voellmy-Perla equation (Irgens et al, 1998). Strictly speaking, the centre-of-mass is that of a representative frontal part of the slide projected onto the terrain, which is hard to define (the total avalanche centre-of-mass may not even reach the dam). The simplified dam geometry consists of a plane terrain of inclination β and the upper plane wall of the deflecting dam, oriented by its angle relative to the terrain, ψ, and the angle between the base line of the dam wall (the x-axis), and the terrain contour lines, φ, see Fig. 2. φ is deduced from the horizontal map projection φ_h, i.e. $\varphi = \cos^{-1}(\cos\varphi_h \cos\theta)$, where $\cos\varphi_h = a/b$ and $\theta = \tan^{-1}(h/b)$. The lengths a, b, and h are all easily deduced from the map, cf. Fig. 3. Using φ_h instead of φ gives conservative run-up estimates in steep terrain.

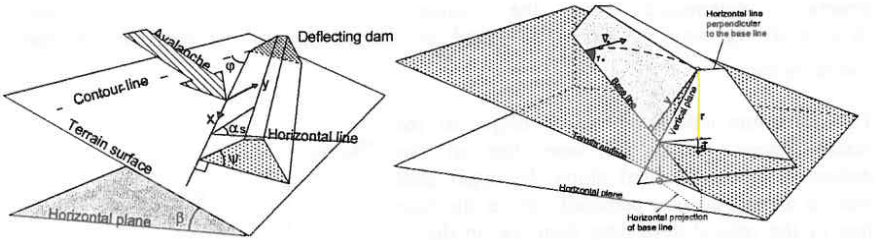

Figure 2. Left: Simplified geometrical configuration for the centre-of-mass model. Right: Principal sketch of run-up heights on deflecting dam. Curved dotted line indicates centre-of-mass path (line may alternatively be interpreted as outer extension of avalanche flow) on the wall of the dam. y (i.e. y_{max}, alternatively the observed height y_{obs}) is the run-up height measured along the terrain in a cross-section perpendicular to the base line of the dam, while r (i.e. r_{max}, alternatively the observed vertical height r_{obs}) is the vertical run-up height measured in a vertical cross-section perpendicular to the horizontal projection of the base line of the deflecting dam.

Stability of the dam puts constraints on the steepest inclination $\alpha_s = \sin^{-1}\left[(g_x/g)^2 + (g_y/g)^2\right]^{1/2}$ along the upper wall of the dam. $g_x = g\sin\beta\sin\varphi$ and $g_y = -g(\cos\beta\sin\psi - \sin\beta\cos\varphi\cos\psi)$ are components of the gravitational force per unit mass, g, in the upper wall plane parallel and normal to the base line, respectively.

The tangential and normal components of the centre-of-mass momentum equations are

$$\frac{dv}{dt} = g_x\cos\gamma - g_y\sin\gamma - \mu g_z - D/M\cdot v^2 \qquad (1)$$

and

$$\frac{v^2}{R} = g_x \sin\gamma + g_y \cos\gamma \qquad (2)$$

respectively, where v is the centre-of-mass velocity at time t and $g_z = -g(\cos\beta\cos\psi + \sin\beta\cos\varphi\sin\psi)$ is the component of g normal to the wall plane. γ is the angle between the centre-of-mass path tangent line and the base line, and R is the radius of curvature of the centre-of-mass path line on the wall. By means of the kinematic condition $v^2 / R = -v \cdot (d\gamma / dt)$ and the transcription $dv / dt = (dv / d\gamma) \cdot (d\gamma / dt)$, eqs. (1) and (2) can be combined into:

$$\frac{dv}{d\gamma} = -\left(g_x \cos\gamma - g_y \sin\gamma - \mu g_z - D / M \cdot v^2\right) v / \left(g_x \sin\gamma + g_y \cos\gamma\right), \qquad (3)$$

which is solved numerically by a fourth order Runge-Kutta procedure. The angle γ is reduced by constant increments $d\gamma$ throughout the simulations. For each new pair of (v, γ) values, the centre-of-mass is moved a distance $ds = v \cdot dt$ along the upper wall in the direction determined by the value of γ. The time increment $dt = -v \cdot d\gamma / (g_x \sin\gamma + g_y \cos\gamma)$ is found by combining eq. (2) and the kinematic condition above.

The maximum calculated run-up height of the centre-of-mass above the base line of the deflecting dam, measured along the upper dam wall in a cross-section perpendicular to the base line of the natural deflecting dam, i.e. in the y-direction, is termed y_{max}. This corresponds to a maximum vertical run-up height above the base line of the deflecting dam, r_{max}, measured in a vertical cross-section perpendicular to the horizontal projection of the base line of the natural deflecting dam, Fig. 2. r_{max} is the run-up height estimated from maps and intuitively pointed out in the terrain. It also the most convenient height for dam design, and is expressed by

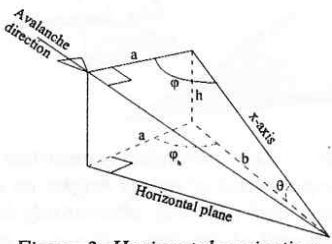

Figure 3: Horizontal projection, φ_h, of the angle φ between the base line of the wall (the x-axis) and the terrain contour lines.

$$r = y\left(\sin\psi\cos\beta - \cos\psi\sin\beta\cos\varphi + \tan\xi\sin\varphi\sin\beta\right), \quad \xi = \cos^{-1}\left[\left(g_y^2 + g_z^2\right)\left(g^4 - g_x^2 g^2 - g_x^2 g_z^2\right)^{-\frac{1}{2}}\right] \qquad (4)$$

Also the effects of energy dissipation due to impact may be investigated by the deflecting dam model. The angle between the centre-of-mass path tangent line on the upper dam wall and the dam base line is $\gamma_0 = \tan^{-1}\left[\left(\cos^2\varphi\cos^2\psi + k^2\cos^2\varphi\sin^2\psi\right)^{1/2} / \sin\varphi\right]$, Fig. 2. The initial centre-of-mass velocity on the upper dam wall (in the direction determined by γ_0), is $v_0 = v_T\left(\sin^2\varphi + \cos^2\varphi\cos^2\psi + k^2\cos^2\varphi\sin^2\psi\right)^{1/2}$. Without any energy dissipation (k=1), the initial values are $\gamma_0 = \pi/2 - \varphi$ and $v_0 = v_T$, respectively. If the centre-of-mass velocity component normal to the upper dam wall is completely lost during the impact (k=0), initial values are $\gamma_0 = \tan^{-1}\left(\cos\psi / \tan\varphi\right)$ and

$v_0 = v_T\left(\sin^2\varphi + \cos^2\varphi\cos^2\psi\right)^{1/2}$. For further details on the deflecting dam model equations, see Harbitz and Domaas (1999).

Run-up height calibration

Domaas and Harbitz (1998) compare centre-of-mass computations to observations. The deviation between observed and calculated values increases with the run-up heights as depicted in Fig. 4. There is no connection between the two that can be physically simply deduced. This reflects the shortage of a centre-of-mass deflecting dam model, i.e. the volume and/or the extension of the avalanche are not considered. Both quantities presumably increase the run-up heights when they get larger, as the following and the lower neighbouring parts of the avalanche push the deflected front upwards.

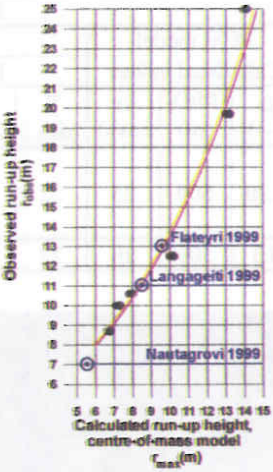

Figure 4: Observed versus calculated run-up heights.

To compensate for the limitations of a centre-of-mass consideration and to provide a simple method to estimate the required height for a deflecting dam, Fig. 4 further presents a best-fit line for the observed run-up heights, r_{obs}, versus the calculated ones, r_{max}, for avalanches with r_{obs}< 25 m, i.e. within dam heights most likely to be built. The line is given by

$$r_{obs} = 3.60 \cdot e^{0.13 \cdot r_{max}} \qquad (5)$$

In the practical applications below, the calculated run-up heights, r_{max}, are calibrated according to Eq. (5) to give the run-up height, r_{cal}, used as a minimum design criteria. In spite of its simplicity, this method takes account of the terrain parameters, the avalanche motion including energy loss, and the dam configuration and orientation.

The observations presented in Fig. 4 are all made in coastal regions with little snow in the lower part of the paths. In regions where more snow can be expected along the dam prior to an avalanche, the dam height should be increased correspondingly.

THE NAUTAGROVI AND LANGAGEITI DEFLECTING DAMS

The two deflecting dams are built in Gudvangen, Aurland Municipality, western Norway, in 1988, Fig. 5 and 6.

Design of the Nautagrovi dam

The dam in Nautagrovi is located in relatively gentle terrain, Fig. 6. The average inclination is β=22°. The dam protects a hotel. It is built in a traditional fashion, with a large dam height of 14 m due to a relatively large angle of incidence of 34° ($\varphi = 90^0 - 34^0 = 56^0$). The dam is 300 m long and has a volume of 60 000 m^3. Tab. 1 shows the values used to calculate the minimum design height of the dam, r_{cal}=7.5 m. A value of k=0.5 was selected for fast dry avalanches with design velocities of 25 m/s owing to the large angle of incidence. The design height was increased to 14 m because more than

one avalanche can be expected each winter, and wet snow avalanches may deposit in the upper part of the gentle channel.

Table 1: Parameter and calculated values describing avalanche path and dynamics used for design of Nautagrovi deflecting dam. Lower row: Back calculation of observations.

Nautagrovi deflecting dam												
PCM model Calculated values			Deflection dam model									
			Parameter values					Calculated values				
μ (—)	M/D (m)	v_T (m/s)	β (deg.)	φ (deg.)	α_s (deg.)	r_{obs} (m)	k (-)	ψ (deg.)	γ_0 (deg.)	v_0 (m/s)	r_{max} (m)	r_{cal} (m)
0.20	500	25	22	56	39		0.0	47.9	24.3	22.7	4.4	6.4
							0.5	47.9	27.3	23.3	5.6	7.5
							1.0	47.9	34.0	25	9.3	12.1
0.3	300	20	22	56	39	7	1.0	47.9	34.0	20	6.1	8.0

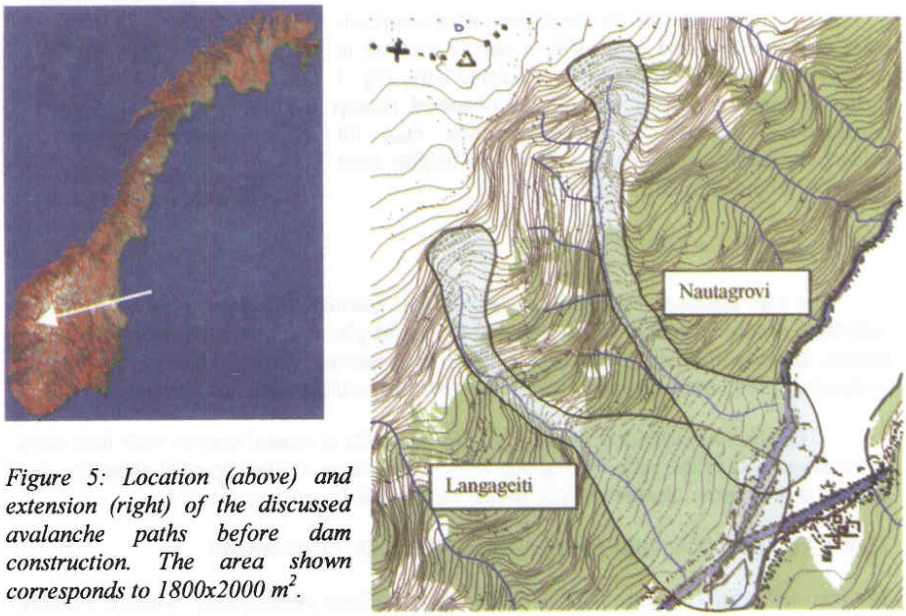

Figure 5: Location (above) and extension (right) of the discussed avalanche paths before dam construction. The area shown corresponds to 1800x2000 m².

Design of the Langageiti dam

The dam in Langageiti is located in steep terrain, Fig. 6. The average inclination in the uppermost part is β=36°. The dam protects a small village along the foot of the talus by the fjord. The dam diverts the whole avalanche from the top of the talus and down past the village. The avalanche is channelled from the top of the talus 350 m a.s.l. and down to 20 m a.s.l. along the dam. The angle of incidence will be 18° ($\varphi = 90^0 - 18^0 = 72^0$) for dry fast avalanches. The dam height is 11 m in the upper part of the talus. The dam is 570m long and has a volume of 80 000 m³. Tab. 2 shows the values used to calculate the minimum design height of the dam in the upper part of the talus, r_{cal}=10.9 m. A value of k=1.0 was selected even for fast dry avalanches with design velocities of about 40 m/s due

to the small angle of incidence.

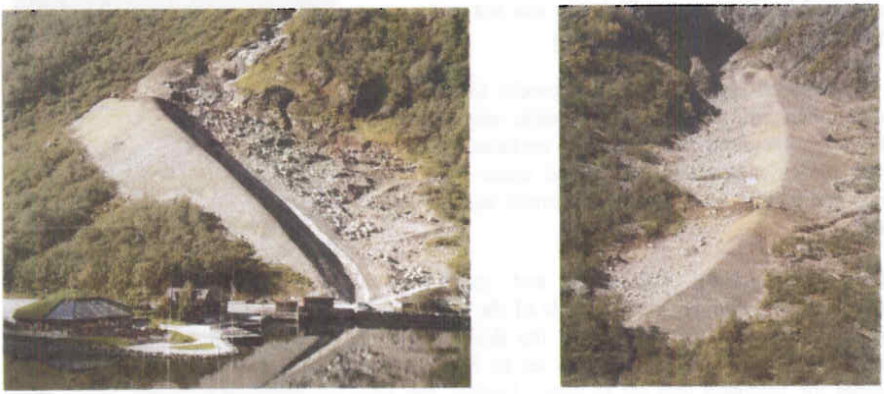

Figure 6: The Nautagrovi (left) and Langageiti (right) dams under construction. The latter is steeper in spite of the impression from the photos.

Table 2: Parameter and calculated values describing avalanche path and dynamics used for design of Langageiti deflecting dam. Lower row: Back calculation of observations.

Langageiti deflecting dam												
PCM model Calculated values			Deflection dam model									
			Parameter values					Calculated values				
μ (—)	M/D (m)	v_T (m/s)	β (deg.)	φ (deg.)	α_s (deg.)	r_{obs} (m)	k (-)	ψ (deg.)	γ_0 (deg.)	v_0 (m/s)	r_{max} (m)	r_{cal} (m)
0.20	500	40	36	72	39		0.0	33.1	15.2	39.4	6.2	8.1
							0.5	33.1	16.0	39.6	6.8	8.7
							1.0	33.1	18.0	40.0	8.5	10.9
0.35	300	27	36	60	39	11	1.0	45.4	30	27	8.7	11.2

The Langageiti dam is situated on top of a natural ridge on the talus, which reduces the contributed volume of the dam. An alternative orientation of the dam with the centre line adjusted twenty meters aside of the talus was considered to increase the channel width. However, the resulting increase in dam volume would cause a two-month increase in construction time.

Soil conditions and stability of the dams

The natural soil deposits in the area of the two dams display a large amount of coarse material, Fig. 7. Soil samples of the finer fractions of the natural deposits (rocks and boulders excluded) were taken in a total of four shafts down to 4 - 5 m below ground level at the planned locations of the two deflecting dams at Nautagrovi and Langageiti.

Grain size distribution curves from all of the samples show that the finer fractions of the natural deposits in general can be described as a sandy, gravely material. In addition, there is a slight tendency to more fines with depth in some of the shafts, and also more fines are found in the upper sections of the scree in which the dams are constructed. The percentage of fines less than 0.075 mm is less than 10 – 15 % for most of the samples, but does in some cases reach to about 25 %.

The depth to the rock surface below ground level was not determined in the scree itself, but was assumed to be located sufficiently low not to have any impact on the stability calculations.

Based on the location of creeks in Nautagrovi and Langageiti, the ground water table was assumed to be below the depth of critical slip surfaces. Further, it was also assumed that the ground water table would not rise significantly during extremely wet periods of the year.

Based on general experience and guidelines in literature, the drained friction angle of the natural soils in the scree was set to 36° and the drained friction angle in the compacted dam was set to 38°. In both cases the cohesion was set to zero. Further, the total unit weight was set to 19 kN/m^3. The selection of friction angles is believed to be somewhat on the conservative side.

Figure 7: Natural soil deposit shows large amount of coarse material.

Stability calculations based on both circular and plane slip surfaces yielded a factor of safety of about 1.5 for the steepest upper part of the Nautagrovi dam. The critical failure mode is part of the dam sliding sideways down the scree, Fig. 6.

The lower part of both dams has a higher factor of safety due to a gentler slope. Because the Langageiti dam more or less follows the steepest descent of the scree, it is judged to be stable as long as the upper part in very steep terrain is resting on the lower part in more gentle terrain, Fig. 6. No specific stability analysis was thus performed for this dam.

Functionality of the dams

Nautagrovi

Two wet avalanches hit the dam in the winter of 1998-99 at estimated velocities of 20 m/s (less than the design velocity v_T=25 m/s) and with estimated volumes of 100 000 m^3 in both events. The observed run-up heights were measured to $r_{obs}\approx$7 m at both occations. The calculated run-up heights with v_T=20 m/s (corresponding to μ=0.3 and M/D=200 m) are r_{cal}=8.0 m, 5.8 m, and 5.2 m for k=1.0, 0.5, and 0.0, respectively, cf. Tab. 1. Wet avalanches favour relatively low energy dissipation, while the large angle of incidence (34°) indicates somewhat higher energy dissipation. With k between 0.5 and 1.0 the resulting r_{cal} is close to the observed run-up height of 7 m.

In the upper part of the dam a small portion of the first avalanche had a larger angle of incidence of 48°. This portion also overtopped the dam. The calculated run-up height for k=1.0 and $\varphi = 90^0 - 48^0 = 42^0$ is r_{cal}= 13 m. This is obviously the critical part of the dam, but lack of loose deposits and steep terrain inclination prevented further expansion.

The second avalanche ran on top of the deposits of the first one, Fig. 8. The avalanche reached the top of the dam and followed just beneath the dam crown all the way down to

the sea. This is probably because the avalanche is wide (~100m) and is forced towards the dam over a long distance. The contour lines of the adjusted terrain on the upper side of the dam are perpendicular to the dam centre line. This will enhance the leading effect of the dam.

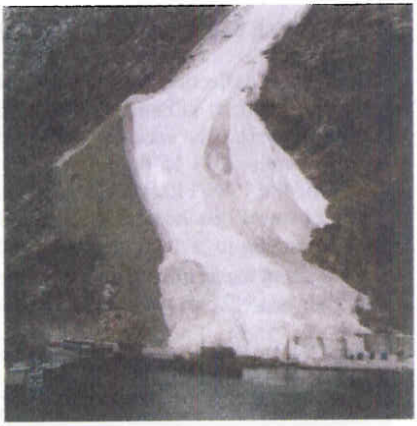

Figure 8: The Nautagrovi dam after the second avalanche during the winter of 1998-99.

Langageiti

Two wet avalanches hit the dam during the winter of 1998-99 at estimated velocities of 27 m/s (less than the design velocity v_f=40 m/s) and with estimated volumes of 60 000 m^3 and 50 000 m^3, respectively. Both avalanches did slightly overtop the dam. The first one left no deposits in the upper part of the channel. Hence the observed run-up heights were $r_{obs}\approx$11 m in both events, Fig. 9. The calculated run-up height with v_f=27 m/s (corresponding to μ=0.35 and M/D=300 m) and an angle of incidence of 30° (φ=60°) is r_{cal}=11.2 m for k=1.0, in close agreement with the observations, cf. Tab. 2. Wet avalanches and small angle of incidence favour small energy dissipation. The angle of incidence is chosen differently than the design value of 72° corresponding to fast dry avalanches, as wet avalanches better follow the depressions in the terrain.

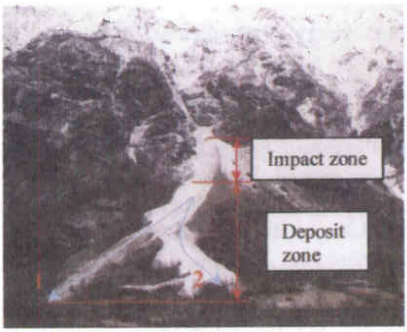

Figure 9: The Langageiti dam after the second avalanche during the winter of 1998-99. Above: The effective height is sustained due to no deposition in the impact zone. The second avalanche overtops the dam in the lower deposit zone. Right: Blow-up of impact and upper deposit zones; arrows: avalanche direction; red line: outer extension of avalanche flow; dotted blue line: outer extension of deposits; light blue area: overtopped deposits of the first avalanche.

THE FLATEYRI DEFLECTING DAM

The Flateyri deflecting dam (Sigurðsson et al 1998) was built after the accidental 1995 Flateyri avalanche killing 20 people (Haraldsdóttir 1998). In February 1999, another dry avalanche struck the recently built dam with an estimated volume of 130 000 m^3, i.e. approximately 25% of the volume of the 1995 event. The observed maximum run-up height of the 1999 Flateyri avalanche was r_{obs}=13 m (Jóhannesson et al 1999). Based on the total travel distance of 1800 m, the impact velocity is back calculated to v_T=42 m/s (corresponding to μ=0.15 and M/D=750 m). Little energy dissipation can be expected at impact given the small angle of incidence of 20° (φ = 70°). This returns a calculated run-up height r_{max}= 9.6 m and a calibrated run-up height r_{cal}=12.5 m from Eq. 5, cf. Tab. 3.

Table 3: Parameter and calculated values from back calculations of the 1999 Flateyri avalanche.

1999 Flateyri avalanche												
PCM model Calculated values			Deflection dam model									
			Parameter values					Calculated values				
μ (—)	M/D (m)	v_T (m/s)	β (deg.)	φ (deg.)	α_s (deg.)	r_{obs} (m)	k (-)	ψ (deg.)	γ_0 (deg.)	v_0 (m/s)	r_{max} (m)	r_{cal} (m)
0.15	750	42	11	70	39	13	0.0	41.6	15.2	40.9	5.5	7.4
							0.5	41.6	16.6	41.2	6.6	8.5
							1.0	41.6	20.0	42.0	9.6	12.5

RUN-UP HEIGHTS BASED ON THE TRADITIONAL ENERGY APPROACH

The traditional assumption that all kinetic energy perpendicular to the dam is transferred to potential energy reveals a run-up height $h = v_T^2 \cos^2 \varphi / 2g$. This approach underestimates the run-up height with 0.8 m, 3.4 m, and 2.7 m with the values used for design criteria in Tables 1-3 for the Nautagrovi, Langageiti, and Flateyri dams, respectively. When using the traditional approach, the run-up height is normally increased to compensate for the flow height and the snow on the ground. With an additional increase of say 3 m for the sake of comparison, the traditional approach reveals run-up heights in close agreement with the observations for the Langageiti and Flateyri events, but overestimates the run-up height in Nautagrovi with more than 2 meters.

The centre-of-mass model indirectly takes the flow height and the snow on the ground into account by calibrating the calculated run-up heights with field observations. In spite of the subjective evaluation needed for the coefficient of restitution, the centre-of-mass model in combination with the calibration procedure seem to return more correct run-up heights.

UPDATED CALIBRATION PROCEDURE

Fig. 4 shows the empirical results from the paper by Domaas and Harbitz (1998), as well as the recent results from the newly built deflecting dams in Flateyri, Iceland and in Gudvangen, Aurland, Norway.

The calculations made for the 1998-99 avalanches in Nautagrovi, Langageiti, and Flateyri are in good agreement with the observations. The data are included in Fig. 4. When the new data are included, the best-fit line for the updated calibration procedure is given by

$$r_{obs} = 3.43 \cdot e^{0.136 \cdot r_{max}} \qquad (6)$$

The coefficient of determination for Eq. 6 is approximately 0.98. The new best-fit line hardly separate from the original one depicted in Fig. 4. Eq. 6 reveals approximately the same calibrated run-up for smaller dams, and less than 1 m higher calibrated run-up for the larger dams within the range of the observations. Eq. 6 gives a calibrated run-up of 12.7 m height at Flateyri, which is slightly better than the height presented above deduced from Eq. 5.

CONCLUDING REMARKS

The recent construction of two avalanche deflecting dams in steep terrain in western Norway has provided new insight into avalanche behaviour and dam design. The fundamentals of avalanche deflecting dams are discussed, with emphasis on optimal location and configuration in the surrounding terrain. The quantities determining avalanche deflection and run-up are studied. It is found that the energy dissipation at impact is of major importance for the run-up.

The design of the two dams is based on a thoroughly described computational/empirical approach convenient for practitioners. In this approach a centre-of-mass model for avalanche motion along the upper wall of a retaining dam is used in combination with six full-scale avalanches observed in terrain formations acting as "natural deflecting dams". Also the soil conditions and stability of the two dams are discussed. The stability of one dam is ensured by a sufficiently high factor of safety, while the other dam more or less follows the steepest descent of the scree and is stable because the upper part rests on the lower part in more gentle terrain.

The functionality of the two dams is analysed based on observations of two avalanches impacting each of the two dams during the winter of 1998-99. The same avalanches are back calculated using the computational/empirical approach. The results are in good agreement with the observations. Similar back calculations are successfully performed for the 1999 Flateyri avalanche in Iceland. The new observations verify the original expression applied to calibrate the run-up heights calculated by the centre-of-mass model, and are finally used for an update of the expression for the best-fit line.

The run-up heights deduced by the computational/empirical approach are compared to run-up heights based on the traditional energy approach. In spite of the subjective evaluation needed for the energy dissipation at impact, the centre-of-mass model in combination with the calibration procedure seem to reduce the uncertainties in the calculations of run-up heights on deflecting dams.

Gathering information on full-scale observations of avalanches deflected by the natural terrain is still of greatest importance for improved understanding of avalanche deflection processes. Future model development should focus on compression, energy dissipation and enlargement into two horizontal dimensions.

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