On avalanche run-up heights on deflecting dams: Centre-of-mass computations compared to observations

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ABSTRACT. This article reports on the observed run-up heights of avalanches in terrain formations that act as "natural deflecting dams" with oblique angle of incidence. To compensate for the deficiencies of today's methods, the parameters governing the run-up heights is discussed, and a computational model based on the Voellmy-Perla equation is used for calculation of the avalanche centre-of-mass path along the deflecting dam wall. The maximum calculated centre-of-mass run-up heights of the avalanches are compared with the observed total run-up heights. The relation between the two types of heights is elaborated upon for various categories of slide volumes.

INTRODUCTION

Increased human activity in mountain regions, deforestation from pollution, forestry and ski resorts as well as a reduced acceptance of living in regions exposed to snow avalanches have caused a growing need for protection against avalanches. Such protection is increasingly obtained by constructing deflecting dams with oblique angle of incidence to influence the dense snow avalanche course. A better knowledge and understanding of terrain deflection of snow avalanches will improve the methods of design and dimension of deflecting dams.

The effects of natural deflecting dams on reported avalanches are described by Harbitz and Domaas (1997; 1998). The most extreme observations indicate that the height difference between the gully floor and the upper limit of extension on deflecting terrain formations might exceed 90 m for large avalanches (estimated volume > 100 000 m^3, reaching a velocity of more than 50 m/s).

Neither the run-up heights pioneered by Voellmy (1955) nor the leading edge models by Hungr and McClung (1987) or Takahashi and Yoshida (1979) contain deflection effects. The papers by McClung & Mears (1995) on dry-flowing avalanche run-up and run-out or the paper by Chu *et al.* (1995) on experiments on granular flows to predict avalanche run-up do not deal with deflection either. Nevertheless, simulations of avalanches on deflecting dams have to take into account that real avalanche flows are three-dimensional. Nohguchi (1989) has developed a three-dimensional dense snow avalanche centre-of-mass model based on the equations of Voellmy (1955), while Sassa (1988) has developed a geotechnical, quasi three-dimensional continuum model. Lang and Leo (1994) developed a quasi three-dimensional dense snow avalanche model, but according to the originators it is still unknown whether the model can represent naturally occurring events. Three-dimensional powder snow avalanche models have been developed by Scheiwiller (1986) and by Tesche (1986), and other three-dimensional Powder snow avalanche models are now being developed into practical tools for avalanche hazard mapping in France (Naaim, 1995), Switzerland (Hermann *et al.*, 1994) and Austria (Brandstätter *et al.*, 1996). Simulations of dense snow avalanches on deflecting dams are discussed by Irgens *et al.* (1997), including a real event simulation comparison between the deflection dam model described below, and a one-dimensional continuum model for three-dimensional avalanche flow. Unfortunately, the present version of the latter model overestimates the run-up heights.

In the present paper, we discuss observed avalanche run-up heights on deflecting dams and suggest a simple computational/empirical method as an alternative to the complex and partly uncalibrated models described above, which are not convenient for practitioners.

ON GOVERNING PARAMETERS

Run-up heights on deflection dams are normally 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 inclination 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 motion prior to impact is determined by the properties and the volume of the flowing masses, and the terrain above the dam. These aspects are more or less reflected by the avalanche velocity immediately before impact. Energy loss and deflection at impact are determined by the coefficient of restitution (also dependent on snow properties), and the orientation and configuration of the dam relative to the terrain, reflected by the velocity difference before and after impact. 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 configuration of the dam relative to the terrain.

THE CENTRE-OF-MASS DEFLECTION DAM MODEL

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 loss due to impact. Consequently, the real value of v_T is perhaps higher than calculated by the PCM model. At the same time, 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 deflection dam model as the best possible choice.

The deflection dam model is another centre-of-mass model based on the Voellmy-Perla equation. 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 wall (the x-axis), and the terrain contour lines, φ, see Fig. 1. The inclination of the line of steepest descent along the upper wall of the dam is $\alpha_s = \sin^{-1}\left[(g_x/g)^2 + (g_y/g)^2\right]^{1/2}$, where $g_x = g\sin\beta\sin\varphi$ and $g_y = -g(\cos\beta\sin\psi - \sin\beta\cos\varphi\cos\psi)$.

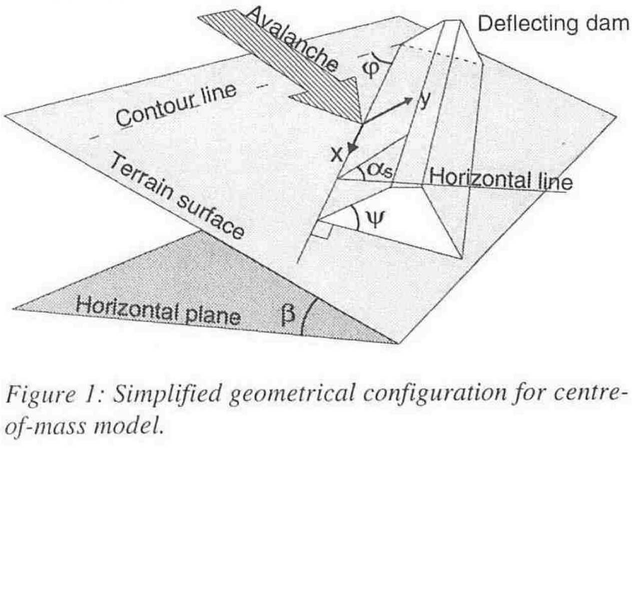

Figure 1: Simplified geometrical configuration for centre-of-mass model.

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. The latter height is more easily estimated from maps, is intuitively pointed out in the terrain and most convenient in dam design. The ratio between the total observed run-up height y_{tot} (or the corresponding r_{tot}) and y_{max} (or r_{max} respectively) is termed the run-up factor $R = y_{tot}/y_{max} = r_{tot}/r_{max}$. The determination of R is discussed in the conclusions. Note that all observed values are encumbered with uncertainties due to obvious problems in making exact measurements with simple and portable equipment.

Also the effects of energy loss due to impact may be investigated by the deflection dam model. The angle between the centre-of-mass path tangent line on the upper dam wall and the dam base line is

$$\gamma_0 = \tan^{-1}\left[\left(\cos^2\varphi\cos^2\psi + k^2\cos^2\varphi\sin^2\psi\right)^{1/2} / \sin\varphi\right],$$

where k is the coefficient of restitution, see Fig. 2. The initial centre-of-mass velocity on the upper dam wall (in the direction determined by γ_0), is

$$v_0 = v_T\left(\sin^2\varphi + \cos^2\varphi\cos^2\psi + k^2\cos^2\varphi\sin^2\psi\right).$$

Without any loss of energy (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 $\gamma_0 = \tan^{-1}(\cos\psi/\tan\varphi)$ and $v_0 = v_T\left(\sin^2\varphi + \cos^2\varphi\cos^2\psi\right)^{1/2}$. For further details on the deflection dam model equations, see Irgens *et al.* (1997); Harbitz and Domaas (1998).

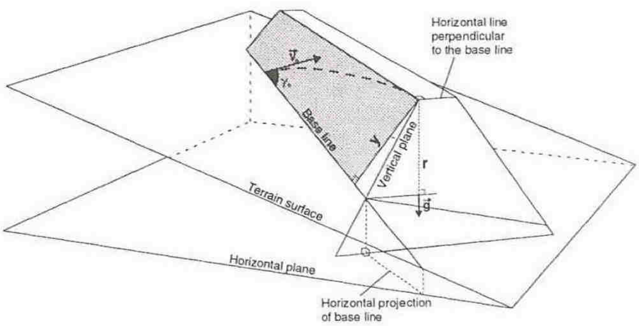

Figure 2: Principal sketch of run-up heights on deflecting dam. Curved dotted line indicates centre-of-mass path (line may alternatively be interpreted as outer extension of avalanche flow) on the wall of the dam. y (i.e. y_{max}, alternatively y_{tot}) is the run-up height measured along the terrain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

CENTRE-OF-MASS COMPUTATIONS COMPARED TO OBSERVATIONS

Twelve avalanche paths are inspected and mapped mainly based on the damage to the forest. The characteristic features of the avalanche and the terrain are referred to in Table 1, including the velocity immediately before impact as calculated by the PCM model.

Of the twelve avalanches, ten were deflected by the terrain, while the Storegjølet and the Årsæterstøylen avalanches passed over the deflection dam apparently without deflection. The latter continued almost to the α-point of the statistical/topographical model (Lied and Bakkehøi, 1980; Bakkehøi *et al.*, 1983; SAME model survey report, 1998). With the same parameter values and without the dam, the avalanche would have continued another 150 m, i.e. half a standard deviation according to the statistical/topographical model. The results further reveal that the velocity is approximately halved by the dam.

The Indre Standal avalanche is deflected twice on its way (termed upper and lower deflection in Table 1). With an increased deflection (φ reduced) and a significantly more gentle dam slope, α_s, the avalanche reaches a larger run-up height in the lower deflection in spite of a much smaller impact velocity, v_T. Also the Lillestølsætra avalanche reaches a large run-up height on a gentle dam slope and a relatively low impact velocity. This emphasises the importance of a steep dam slope causing high energy loss at impact.

Table 1 further reveals the observed run-up heights, r_{tot}, and the run-up heights calculated by the deflection dam model, r_{max}. There is no obvious connection between the two that can be physically simply deduced. The calculated run-up heights strongly depend on the energy loss at impact, described by the value of k. It is observed that smooth deflection (relatively large local radius of curvature at impact), gentle dam slope and wet snow (low compression) favour low energy loss, i.e. high values of k, and large run-up heights.

With the k values in Table 1, the deviation between observed and calculated values increases with the run-up heights, see Fig. 3. This reflects the shortage of a centre-of-mass deflection 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.

To overcome this problem and provide a simple method to estimate the required height for a deflecting dam, Fig. 3 further presents a best-fit line between the points describing all avalanches deflected by the terrain. Only the Tomasjorddalen avalanche with the extreme value r_{tot}=91 m is omitted. However, with k=0.5 the calculations will fit in fairly well along the curve also here. In spite of its simplicity, the method takes account of the terrain parameters, the avalanche motion including energy loss, and the dam configuration and orientation.

To provide a better best-fit line for smaller run-up heights and for dams more likely to be built, Fig. 4 reveals the results for avalanches with observed run-up values less than 25 m only.

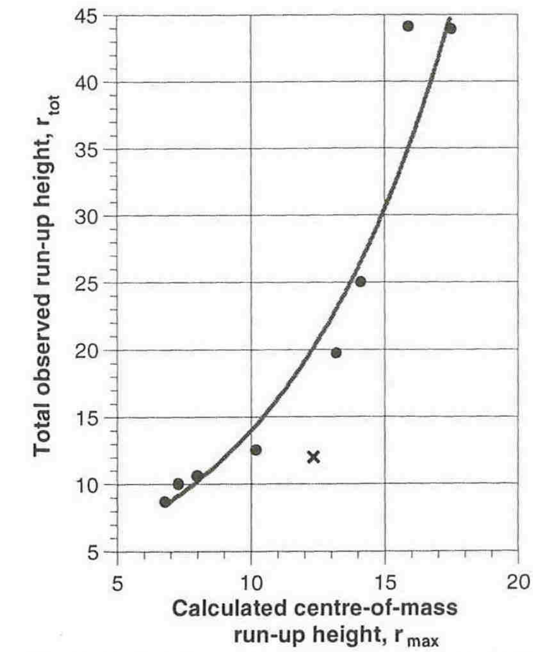

Figure 3: Calculated centre-of mass run-up heights compared to observed run-up heights. Line shows best-fit relation $r_{obs} = 2.93e^{0.16 r_{max}}$ *with the avalanche "Indre Standal L" (✖) excluded.*

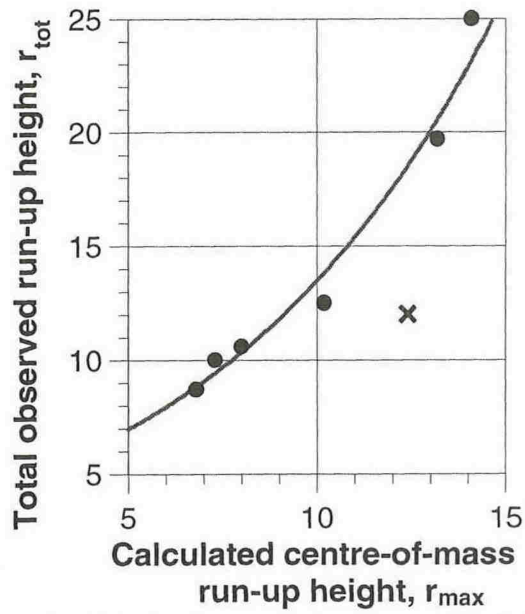

Figure 4: Calculated centre-of mass run-up heights compared to observed run-up heights for the avalanches with r_{tot} < *25.0 m. Line shows best-fit relation* $r_{obs} = 3.60e^{0.13 r_{max}}$ *with the avalanche "Indre Standal L" (✖) excluded*

CONCLUDING REMARKS

Field observations of avalanches directed by natural deflection dams are back-calculated by a simple centre-of-mass model using the Voellmy-Perla equation.

Large run-up heights are reached by avalanches with big volumes/and or extension which obtain high velocities. These slide dimensions are not accounted for in a centre-of-mass model, though the latter certainly accounts better for small and narrow avalanches. Hence, the deviation between observed and calculated values increases with the run-up heights. It is also noted that abrupt local deflection and/or steep dam slopes favours small run-up heights. This is probably because a large degree of compression takes place, which must be considered in estimating the dam heights. On the other hand, low energy loss seems to occur for large, wet and slow avalanches smoothly deflected, presumably not being much compressed at impact.

To overcome the shortages of a centre-of-mass model, a best-fit line between the observed and the calculated run-up heights is suggested for practical dam design. Furthermore, the centre-of-mass model provides additional information on where the maximum run-up height is obtained along the dam wall.

The gathered observational information provides a substantial basis for improved understanding of avalanche deflection processes. Such understanding is essential for further development, validation and verification of continuum avalanche models, and for dam design.

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REFERENCES

Bakkehøi, S., U. Domaas, and K. Lied. 1983. Calculation of Snow Avalanche Run-out Distance. *Annals of Glaciology*, Vol. **4**, 24–29. Also in: *Norwegian Geotechnical Institute*, publication no. **151**, 1984.

Brandstätter, W., G. Hagen, H. Hufnagel, and H. Schaffhauser. 1996. Ein gasdynamisches Lawinensimulationsmodell. *Proceedings INTERPRAEVENT 96, Garmisch Partenkirchen.*

Chu, T., G. Hill, D.M. McClung, R. Ngun, and R. Sherkat 1995. Experiments on granular flows to predict avalanche runup. *Canadian Geotechnical Journal* **32**, 285–295.

Harbitz, C. and U. Domaas. 1997. Runout distance: Mapping of natural deflecting dams. *Norwegian Geotechnical Institute*, report **581210–1,** 3 January 1997.

Harbitz, C. and U. Domaas. 1998. Run-out distance: Mapping of natural deflecting dams - validation of numerical models. *Norwegian Geotechnical Institute*, report **581210–2**, in preparation.

Hermann, F., D. Issler, and S. Keller. 1994. Towards a numerical model of powder snow avalanches. *In:* S. Wagner *et al.* (eds.), *Proc. 2nd Europ. Comp. Fluid Dynamics Conf., Stuttgart, 1994,* 948–955. J. Wiley & Sons, Ltd., Chichester, UK.

Hungr, O. and D.M. McClung. 1987. An equation for calculating snow avalanche run-up against barriers in avalanche formation, movement and effects. *Proceedings, Davos Symposium, 1986. International Association of Hydrological Sciences*, Publication **162**, 605–612.

Irgens, F., B. Schieldrop, C. Harbitz, U. Domaas, and R. Opsahl. 1997. Simulations of dense snow avalanches on deflecting dams. *Annals of Glaciology*, Vol. **26**, in press. Also in: *Norwegian Geotechnical Institute*, report **581210–3**.

Lang, R.M. and R. Leo. 1994. Model for avalanches in three spatial dimensions - Comparison of theory to experiments. *Cold regions research and engineering laboratory* report **94–5**.

Lied, K. and S. Bakkehøi. 1980. Empirical Calculations of Snow-Avalanche Run-Out Distance Based on topographic Parametres. *Journal of Glaciology*, Vol. **26**, No. **94**, 165–177. Also in: *Norwegian Geotechnical Institute*, publication no. **133**, 1981.

McClung, D.M. and A.I. Mears. 1995. Dry-flowing avalanche run-up and run-out. *J. Glaciol.* **41** (138), 359–372.

Naaim, M. 1995. Modélisation numérique des avalanches aérosols. *La Houille Blanche* Nr. 5/6–1995, 56–62.

Nohguchi, Y. 1989. Three-dimensional equations for mass centre motion of an avalanche of arbitrary configuration. *Annals of Glaciology* Vol. **13**, 215–217.

Perla, R.I., T.T. Cheng, and D.M. McClung 1980. A Two-Parameter Model of Snow–Avalanche Motion. *Journal of Glaciology* Vol. **26**, No. **94**, 197–207.

Sassa, K. 1988. Geotechnical model for the motion of landslides. *Proceedings of the Fifth Int. Symp. on Landslides, Lausanne.* (Bonnard, C. ed.). Vol. **1**, 37–56.

SAME model survey report, 1998. A survey of computational models for snow avalanche motion. (Harbitz, C., ed.). *Norwegian Geotechnical Institute*, in preparation.

Scheiwiller, T. 1986. Dynamics of Powder Snow Avalanches. *Ph.D. thesis.* Available as: *Mittlg. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Swiss Federal Institute of Technology Zurich*, Nr. **81**, 115 p.

Takahashi, T. 1991. Debris flow. *International Association of Hydraulic Research. A.A. Balkema, Rotterdam, The Netherlands.*

Takahashi, T. and H. Yoshida. 1979. Study on the deposition of debris flows, Part I – Deposition due to abrupt change of bedslope. *Annals, Disaster Prevention Research Institute, Kyoto University, Japan,* **22 B–2** (In Japanese with English abstract). See Takahashi (1991) for English translation.

Tesche, T.W. 1986. A three dimensional dynamic model of turbulent avalanche flow. *Proc. Int. Snow Science Workshop, Lake Tahoe California*, 1–27.

Voellmy, A. 1955. Über die Zerstörungskraft von Lawinen. *Schweiz. Bauzeitung* **73**, 159–165, 212–217, 246–249, 280–285.

Table 1: Summary of characteristic features and computational results for the twelve considered avalanches. All symbols explained in text.

Name of Avalanche	Height Start/Stop m a.sl.	β deg.	φ deg.	α_s deg.	ψ deg.	v_T m/s	Estimated volume Start / incl. entrainment $1000m^3$	r_{tot} m	r_{max} m	k [-]	Reasons for for choice of k value	Description of avalanche (assumed)
Åpoldi G	1300 / 0	21.8	53.6	42.3	52.5	31.8	80 / 250	44.1	15.9	1.0	smooth deflection, large width	dry; dense+powder
Åpoldi L	1300 / 0	21.8	36.3	41.6	57.8	31.8	80 / 250	19.7	13.2	0.5	moderate deflection, large width	dry; dense+powder
Tomasjorddalen	1100 / 0	21.0	33.1	49.0	65.8	51.1	60 / 200	91.0	31.7	0.5	moderate deflection	dry; dense+powder
Årsæterstøylen	1000 / 220	18.4	46.5	37	47.8	43.1	50 / 150	11.8[1]	18.4	0.0	abrupt deflection	dry; dense part with moderate cloud
Lillestølsætra	800 / 195	12.5	44.8	18.4	25.2	32.3	30 / 100	43.9	17.5	1.0	gentle dam slope (causes minor avalanche deflection)	dry; loose dense part with minor cloud
Vassdalen	470 / 210	26.5	50.0	32.7	44.2	28.0	6 / 12	25	14.1	1.0	smooth defelction	dry, loose dense part with minor cloud
Legdefonna	1400 / 420	38.3	67.4	35.5	23.8	38.5	40 / 100?	10.0	7.3	1.0	smooth deflection, wet	wet; dense
Indre Standal U	1300 / 0	29.0	48.8	46.0	61.8	40.4	30 / 50	10.6	8.0	0.0	abrupt deflection	dry; dense
Indre Standal L	1300 / 0	8.8	30.2	20.3	27.5	23.0	30 / 50	12.0	12.3	1.0	abrupt deflection, but gentle dam slope; second impact	dry(?); dense
Storegjølet	1000 / 120	20.5	36.5	41.4	56.6	59.1	25 / 50	8.0[1]	30.6	0.0	abrupt defelction	dry; dense
Sauresetra	600 / 375	18.4	63	29.7	33.7	33.5	10 / 20	12.5	10.2	1.0	smooth and minor deflection	dry; dense
Gaukheidalen	375 / 50	21.8	65.1	36.0	40.3	34.5	7 / 15	8.7	6.8	0.5	moderate deflection, large width	dry; dense

1) Avalanche passes dam apparently without deflection. Number indicates dam height.