

## FORCES ON STRUCTURES IMPACTED AND ENVELOPED BY AVALANCHES

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**ABSTRACT.** A computer code is reported that models two-dimensional flow of a snow-avalanche cross-section over a down-slope structure of arbitrary cross-sectional shape. Impact forces and pressure are predicted, and the flow pattern past the structure may be arrayed pictorially. The model is applied to the prediction of forces on rectangular obstacles which are of fractional height to the nominal avalanche flow depth for avalanche flow speeds up to 20 m/s. The program is applied to modeling an experiment by Salm of impact of snow blocks upon a slope-normal wall in order to demonstrate the accuracy of the code in comparison to impact-force histories measured by Salm. Difference between the experimental results and the computer simulation is less than 21%, and supporting discussion is given on factors that may account for the difference.

**RÉSUMÉ.** *Forces s'exerçant sur une structure heurtée et entourée par des avalanches.* On présente un programme de calculateur qui simule l'écoulement bi-dimensionnel d'une section en travers d'une avalanche de neige sur un obstacle à l'aval de section variable. On prévoit les forces et les pressions à l'impact, et l'on peut représenter visuellement par des flèches le comportement de l'écoulement au passage de l'obstacle. On applique le modèle à la prévision des forces sur des structures rectangulaires dont les hauteurs sont des fractions de la hauteur totale de l'avalanche pour des vitesses d'avalanches allant jusqu'à 20 m/s. On applique le programme à la modélisation d'une expérience menée par Salm du choc de blocs de neige sur un mur perpendiculaire à la pente en vue de démontrer la précision du programme en comparaison avec les forces d'impact réellement mesurées par Salm. La différence entre les résultats expérimentaux et la simulation par l'ordinateur est inférieure à 21% avec des discussions possibles sur les facteurs qui peuvent expliquer la différence.

**ZUSAMMENFASSUNG.** *Kraftwirkungen auf Bauwerke, die von Lawen angefahren und eingehüllt werden.* Es wird über ein Rechenprogramm berichtet, das den zweidimensionalen Fluss eines Lawinenquerschnitts über ein hangabwärts liegendes Bauwerk mit beliebiger Querschnittsform modelliert. Die Kräfte und der Druck des Aufpralls werden berechnet; das Fließmuster hinter dem Bauwerk kann bildmässig dargestellt werden. Das Modell wird zur Berechnung der Kräfte auf rechteckige Hindernisse verwendet, deren Höhe einen Bruchteil der nominellen Lawinenhöhe beträgt; die Fließgeschwindigkeit kann bis zu 20 m/s betragen. Eine Anwendung gilt der Simulation eines Versuches von Salm über den Aufprall von Schneeblocken auf eine hangparallele Mauer; sie ermöglicht eine Beurteilung der Genauigkeit des Programms durch Vergleich mit dem von Salm gemessenen Verlauf der Aufprallkräfte. Der Unterschied zwischen den Versuchs- und Rechenergebnissen liegt unter 21%. Die Faktoren, von denen diese Differenz herrühren kann, werden diskutiert.

### INTRODUCTION

A methodology for the prediction of forces and pressures on structures subjected to snow-avalanche impact is developed in this paper. The case of initial impact, in which the shape of the leading edge of the avalanche controls the nature of the face build-up on a structure, has been developed by Lang and Brown (1980). The case considered here is that of initial impact, followed by overflow of the structure as the transient flow envelops the structure. The computer code developed to carry out this analysis is versatile so far as the specific geometry of a structure that can be represented is concerned. The two-dimensional flow profile can be multi-surfaced as when overflow occurs or when particles of snow impact and splash. Direct application of the program to the analysis of impact upon abutments, avalanche sheds, avalanche defense structures, and related structures is straightforward, requiring only some knowledge of programming with the Fortran computer language.



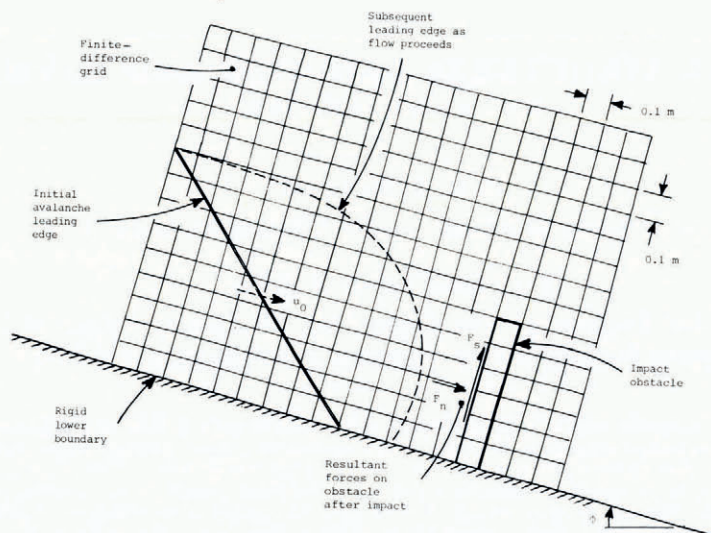


Fig. 1. Physical description of avalanche and impact obstacle.

#### DESCRIPTION OF PROBLEM

The requirements for the equilibrium flow of snow on a slope have previously been described by Lang and others (1979). For given surface-friction and kinematic-viscosity coefficients, snow flow will be uniform at a nominal velocity  $u_0$  only at a specific slope angle  $\phi$  (Fig. 1). For example, to have a nominal flow velocity of  $u_0 = 20$  m/s, with surface friction set at  $f = 0.5$  and viscosity at  $\nu = 0.5$  m<sup>2</sup>/s, then  $\phi$  must equal  $30^\circ$ . An initial sloping, straight-edged snow mass based upon this set of parameters will transform into the dashed-line shape shown in Figure 1 after one cycle of calculations using the computer code developed for the present analysis. This leading edge will change continuously as the finite-difference Navier-Stokes equations are applied together with the imposed conservation of mass and momentum to predict the advancement of the flow of this viscous, incompressible fluid. In the present study, details of the shape of the leading edge of the avalanche are not important, unlike the case considered by Lang and Brown (1980), since the primary concern is for the average forces that develop as the flow overflows and envelops the structure. A typical flow sequence is that shown in Figure 2 which is the actual computer printout for an avalanche one meter deep impacting a 0.6 m high obstacle at a nominal impact speed of 15 m/s. The time variations of the total slope-parallel and slope-normal forces on the obstacle are shown in Figure 3. The transient-force response occurs over the initial 0.3 s of impact, then settles to a slowly decaying value as the avalanche overflows the obstacle.

The magnitude of the transient response depends primarily upon the shape of the avalanche leading edge and is not considered further in this paper. Instead, we consider the secondary force response which is slowly decaying, and its variation as the obstacle height is varied relative to avalanche flow depth. The secondary force is computed as the average force after the initial transient and for up to 100 ms after the impact. During this interval of time the flow does not become steady, so that the secondary forces are larger than steady flow values.

The primary parameters influencing force on the obstacle are flow speed, snow density, and height of the obstacle relative to the avalanche flow depth. Surface friction and kinematic viscosity affect principally the speed and wave-front profile of the incident avalanche, for which data are insufficient to draw any effective conclusions as to parameter values. Fluid compressibility, excluded in the present investigation, would, if included, tend to lower impact

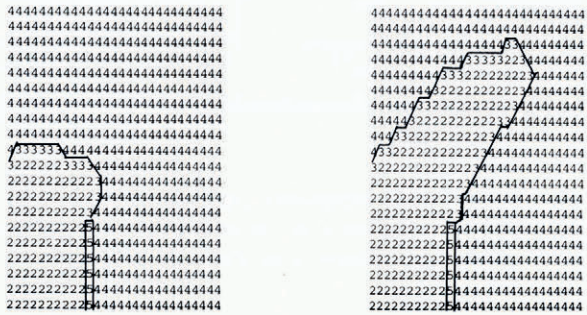
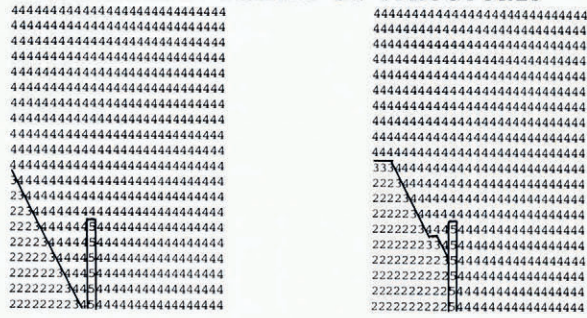


Fig. 2. Computer output of avalanche impact (lines added for emphasis). Cell designations are: 2 = full cell, 3 = surface cell, 4 = empty cell, and 5 = obstacle cell.

- a (upper left). Pre-impact ( $t < 0$  s).
- b (upper right). Early impact ( $t = 0.001$  s).
- c (lower left). Early overflow ( $t = 0.036$  s).
- d (lower right). Continued overflow ( $t = 0.088$  s).

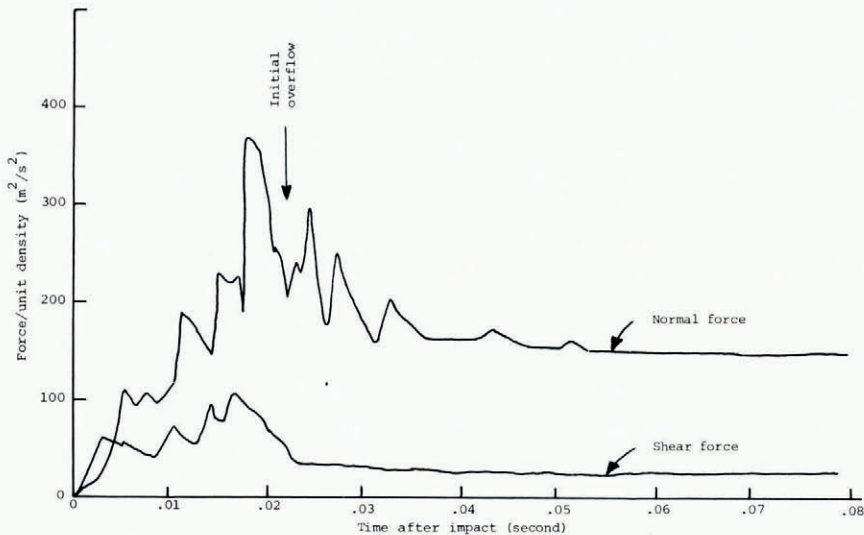


Fig. 3. Normal- and shear-force variation with time for impact of a 1.0 m-deep avalanche against a 0.6 m-high slope-normal obstacle at a nominal flow velocity of 15 m/s.



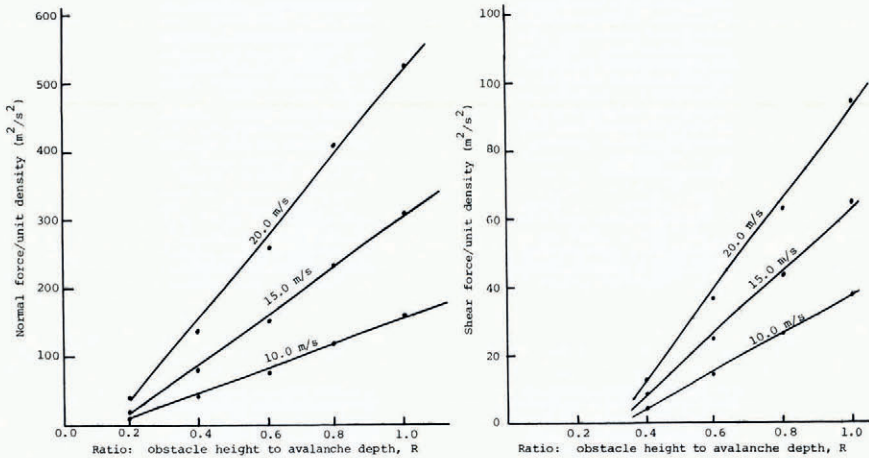


Fig. 4. Secondary normal- and shear-force variation with avalanche velocity for different obstacle heights relative to avalanche flow depth.

pressures (except in the case of wave reflection and reinforcement in a specific structural design). Fluid compressibility is considered to be a secondary factor in the light of current comparisons with experimental data discussed in the following section.

#### ANALYTICAL RESULTS

Average values of the secondary normal and shear forces are plotted against  $R$ , the ratio of obstacle height to avalanche depth, for impact velocities of 10, 15, and 20 m/s in Figure 4. If straight-line approximations are selected to represent the three variations, then the corresponding equations for normal force are:

$$\left. \begin{aligned} F_n &= \rho(180R - 20) & \text{for } v = 10 \text{ m/s,} \\ F_n &= \rho(355R - 45) & \text{for } v = 15 \text{ m/s,} \\ F_n &= \rho(605R - 80) & \text{for } v = 20 \text{ m/s,} \end{aligned} \right\} 1.0 \geq R \geq 0.2$$

and for shear force

$$\left. \begin{aligned} F_s &= \rho(53R - 16) & \text{for } v = 10 \text{ m/s,} \\ F_s &= \rho(93R - 28) & \text{for } v = 15 \text{ m/s,} \\ F_s &= \rho(133R - 40) & \text{for } v = 20 \text{ m/s,} \end{aligned} \right\} 1.0 \geq R \geq 0.4.$$

In these equations,  $\rho$  is the density of the impacting snow. These equations can be further consolidated by incorporating the velocity dependence as follows:

$$F_n = 0.2 \rho v^2 \left( \frac{16R}{v^{0.25}} - 1 \right), \quad 0.2 \leq R \leq 1.0,$$

$$F_s = 2.75 \rho v^{1.3} (R - 0.3), \quad 0.4 \leq R \leq 1.0,$$

in these equations force is measured in newtons if density is in  $\text{kg/m}^3$ .

#### DISCUSSION OF RESULTS

The computer code adapted in the present analysis has been verified as representing fluid flow for a number of different fluid configurations by Amsden and Harlow (1970). The results reported above are stable with respect to convergence based upon grid size. The grid size

used in all the above calculations was 0.1 m (Fig. 1), and near-identical results were obtained for a grid dimension of 0.5 m. Accuracy of the reported results relative to the assumed model for snow is currently being investigated. Model tests are presently in progress to verify both the fluid description for snow, and its impact characteristics with rigid structures.

One experimental investigation has been reported in sufficient detail that a comparison can be made with the computer formulation. The experimental results are those of Salm (1964), in which rectangular blocks of high-density snow ( $\rho = 530 \text{ kg/m}^3$ ) were impacted against a slope-normal wall at a speed of 12 m/s. Test number 3/61 of Salm's reported experiments can be compared to our computer simulation of the same problem. This test of Salm's is the only one of six reported in which the impacting block remained intact during the test. The two response curves for slope-parallel average normal stress per unit density are shown in Figure 5. Initial transient response for the two cases is different, as expected, since

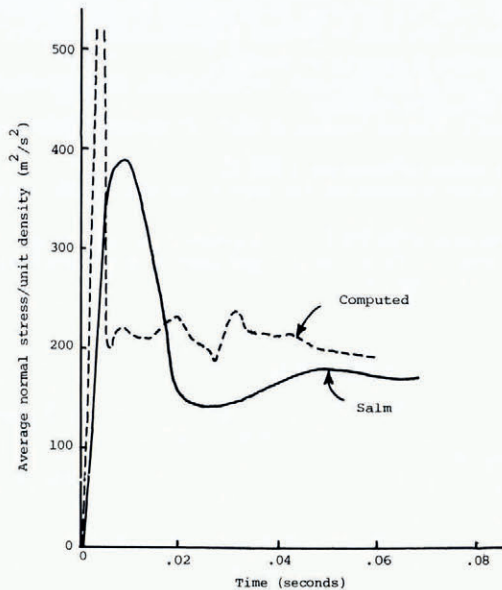


Fig. 5. Computed normal stress compared to experimentally measured values. Block impact velocity = 12 m/s.

the computer simulation is for impact against a rigid wall, whereas the experimental impact, according to Salm, is against an elastic obstacle. Secondary stresses for the two cases are, however, comparable, with an estimated experimental value of  $165 \text{ m}^2/\text{s}^2$  and a computer value of  $200 \text{ m}^2/\text{s}^2$ , a difference of 21%. This error is in the correct direction since, from a physical point of view, Salm's experimental results should show a reduced stress because the frontal cross-section of  $2.5 \times 0.95 \text{ m}^2$  spreads radially at impact, whereas in the computer model it can only spread upward. The 21% difference must include effects of the difference in elasticity of the two impact structures, difference in the lateral-spreading patterns for the two cases, and difference in shape of the leading edges in addition to fluid compressibility effects, although an explicit knowledge of the relative strengths of these effects is not known.

In summary, the computer code, as currently formulated, can be used in evaluation of structures and structural systems. Although the code is a two-dimensional formulation, the indication is that results may be extended to three-dimensional cases in which flow around the ends of the structure is not a large fraction of the flow distribution.



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## APPENDIX

## COMPUTER CODE DESCRIPTION

The computer code modified for the study of avalanche flow was originally reported by Amsden and Harlow (1970) and designated the SMAC code (an acronym for Simplified Marker-And-Cell approach to fluid-flow representation). Modifications made to the code to facilitate impact analysis include:

1. A cell-pressure and force-on-obstacle calculation section.
2. Iteration over only the filled part of the flow grid, and automatic time incrementation.
3. The insertion of a slip-flow boundary condition.
4. On-line printout of flow profile (Fig. 2) in place of alternate printout options that were incorporated in SMAC.
5. Removal of tape dump and restart instructions in SMAC.
6. Removal of other miscellaneous instructions not needed for the specific problem of two-dimensional avalanche impact.

A listing of the modified code, written in FORTRAN IV, together with instructions on use of the code may be obtained by writing to the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521, U.S.A., to the attention of Dr M. Martinelli, Jr.

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