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Computer Study of Startup Dynamics on Wet Snow Avalanches

By

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Abstract

The startup dynamics of three wet snow avalanches which were artificially released by explosives in central Japan were evaluated by computer modeling these occurrences and comparing leading edge position-time data. Results were compared between three finite difference based computer codes, which were used to model the startup transients. Two of the computer codes use equations of uniform flow hydrodynamics, the third transient viscous fluid mechanics. The latter two codes also incorporate a material description of snow as a locking material. Results show a general increasing of frictional and/or viscous coefficients in the avalanche startup zones in order to match the kinematics of startup. Differences in results between the codes are attributed to shape of the startup zones, whether convex or concave. The results indicate the magnitude of perturbation of startup on total avalanche runout time, which is likely to be negligible on long duration avalanche occurrences.

All analytical results are contained in this report.

1. Introduction

In development of analytically based methods for snow avalanche dynamics little attention has been focused on avalanche startup. The primary reason for this has been an apparent lack of experimental data upon which to base comparisons. However, data has been collected for approximately two decades on measurement of snow avalanche startup dynamics. The work was done by Shoda with a team of associates in the 1960's and 70's at three different mountain locations in Japan. In these experiments deep snow releases were obtained by use of explosives, to either initiate cornice fall or to unsettle snow slab, or both. Prior to the artificial release, the snow slope was in a stable condition, so that extensive measurements could be made of snow depth and distribution, snow stratification

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and density, air and snow temperatures, and other related properties. With marker flags emplaced at 20 m intervals along the avalanche paths, advance of the released snow was recorded on 16 mm film footage, and by other observational techniques. From these data position-time plots of each avalanche were made, or the data reported from which such plots could be made. The data is accurate from the instant the leading edge of the avalanche emerges from the powder cloud generated by the explosion. This provides data points on early avalanche motion which characterizes the kinematics of the startup. As will be seen the few seconds of motion shrouded by the explosion powder cloud does not detract significantly from measurements that depict the startup transient.

The purposes of this reporting are two-fold. One is to present the data obtained by Shoda and associates in a summary form that is readily applicable to avalanche dynamics analysis. The second is to analyze the avalanche startup dynamics with current numerical methods and determine the parameterization changes that are needed in order to match the experimental and numerical results. Upwards of 22 avalanches were initiated and recorded by Shoda, each with varying degrees of success relative to runout. Of these, a select number of cases for which runout is well-defined, and for which displacement-time profiles could be constructed are reported. For the avalanches considered, all were started by a field array of explosives buried in the starting zone; that is, none were started by cornice fall.

2. Numerical Analysis Programs

Three computer programs are used to model the startup transients of the Shoda avalanches. Program AVALNCH (Lang, Dawson, Martinelli, 1979) models the transient 2-D motion of the snow as a viscous, boundary layer type fluid. The governing equations are the Navier-Stokes equations, namely

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \nabla^2 u$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = g_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \nu \nabla^2 v$$

where

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

The left hand sides of these equations are the fluid acceleration components relative to a control volume. The right hand terms are the fluid driving and motion resistance force intensities. Here, the gravity components are driving force intensities. The pressure gradients are driving terms also if the gradients along coordinate directions are negative. Fluid resistance to motion, or internal dissipation, occurs by viscous action associated with development of shear stresses within the fluid, due to boundary influences. This dissipation is characterized by the terms with coefficient, ν, the kinematic viscosity of the fluid. A recently developed version of the AVALNCH code is used, that incorporates a biviscous material representation of flowing snow (Dent, Lang, 1983). In this program the avalanche path is divided into a uniform grid of cells, each 10 m long for the paths considered herein, and the flowing snow is advanced through the cells by finite difference forms of the equations of motion. Depending upon the mean level of shear stress in each cell that contains moving snow, one of two possible viscosities are assigned to the cells. By this mechanism the locking property of snow at low shear stresses is approximated. That is, at high shear stress levels a small value of viscosity, ν, is assigned to the cell and the material deforms easily. At low shear stress levels (low velocity gradients) a large value of viscosity, ν', is assigned to the cell, and the material deforms less readily (Figure 1). For snow, an order-of-magnitude or greater difference between ν and ν' has been determined from several experimental flow tests (Dent, Lang, 1983), thus the snow effectively locks when ν' is operative. In the computer program that uses these equations, designated BIAV, the lower surface between the flowing and stationary materials is specified as no-slip, the usual fluid mechanics assumption. Thus, this program has a single parameter, viscosity ν (and ν'), that may be varied in application to the startup dynamics problem under consideration.

The second program ACEL (Cheng, Perla, 1979) is based upon equations of uniform flow hydrodynamics for which the particle equation of motion is

$$a = g(\sin\theta - \mu\cos\theta) - D/M\, v^2$$

Here, gravity is driving, and two dissipative mechanisms are assumed. One is dry friction with coefficient μ, and the second is dynamic viscosity, with coefficient D/M, treated as a single parameter. In application to snow the equation was first introduced by Voellmy (1955). In this program an avalanche path is approximated by straight line segments which may be of varying length. The two coefficients of flow dissipation may be assigned single values for the entire length, or separate values for each segment.

The third program BIEQ, (Lang, Nakamura, Dent, Martinelli, 1984) is a modified version of ACEL that incorporates a mechanism for material locking, and a redefinition of the friction and viscous drag coefficients in terms of snow release depth. The governing particle equation is

$$a = g(\sin\theta - \mu_0 h\cos\theta) - \frac{\nu^*}{h^3} v^2$$

where μ_0 is the friction coefficient, h is the average depth of the release snow and $\nu^* = \nu_0\ (1 + 500e^{-1.25V})$ is the viscous locking parameterization for different flow speeds. Viscosity ν_0 is the high speed viscosity corresponding to ν in Figure 1, and acts at flow speeds $v > 8.0\ ms^{-1}$.

In both programs BIEQ and ACEL, two parameters may be varied in application to the startup dynamics problem under consideration. It is noted that in the three programs that are applied to the startup dynamics problem that the parameter values are empirical;

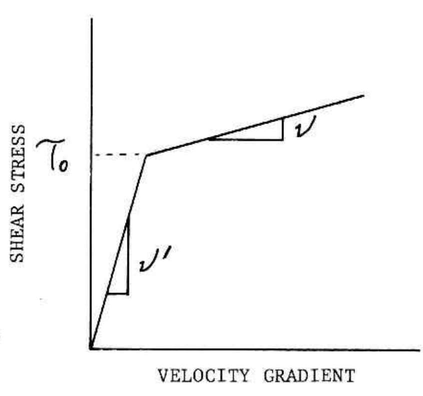


Fig. 1: Biviscous material representation

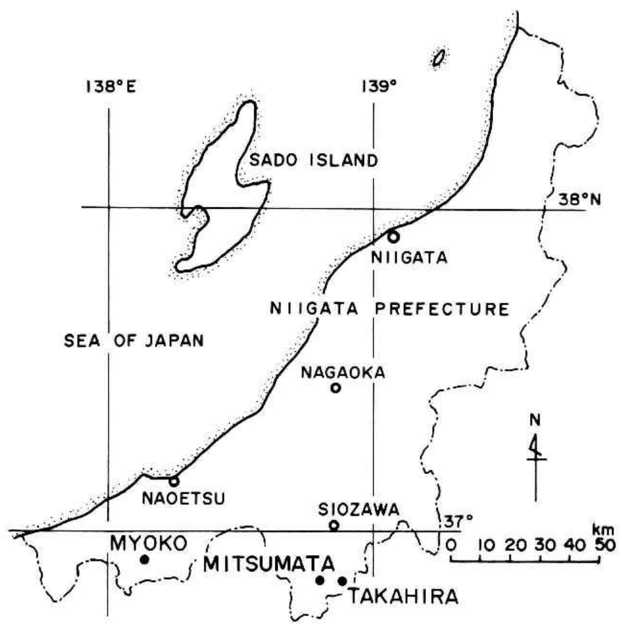


Fig. 2: Location of avalanche test slopes – Central Honshu Island

having no established basis for experimental evaluation. The above three programs were made operational on the Shinjo Branch computer system by one of the authors, T.E. Lang (1984) and used for the following computational analyses.

3. The Avalanche Sites

The three avalanche paths, Takahira, Mitsumata, and Myoko, are located near the west coast of central Honshu, south of the city of Nagaoka, in Niigata Prefecture (Figure 2). Mt. Takahira and the Mitsumata slope are westerly facing, and boarder on a major Japanese rail route and highway, respectively (Figure 3). Mt. Myoko is southeasterly facing. The three sites are exposed to prevailing winds from the Sea of Japan, and are subject to what is termed a coastal environment. Pit data taken at each site on the day of avalanche release, and in proximity to the release zones indicate that the snow was isothermal and wet (Figure 4). Although the pit data does not indicate the release zone depths of the avalanches, the Takahira slab was considerably shallower than either Mitsumata and Myoko. Actual slab release depths were difficult to estimate from field data, and some personal communications were necessary to establish the average depths of snow in the three release zones.

4. Mt. Takahira Avalanche Path

Mt. Takahira, located 62 km from the coast of the Sea of Japan, has an avalanche slope extending from 600 to 900 m elevation (Figure 5). On 6 March 1961 a 1.3 m average depth wet snow slab avalanche was released at the summit of the path (elevation 870 to 890 m). The avalanche followed the dashed line path shown in Figure 5 terminating just

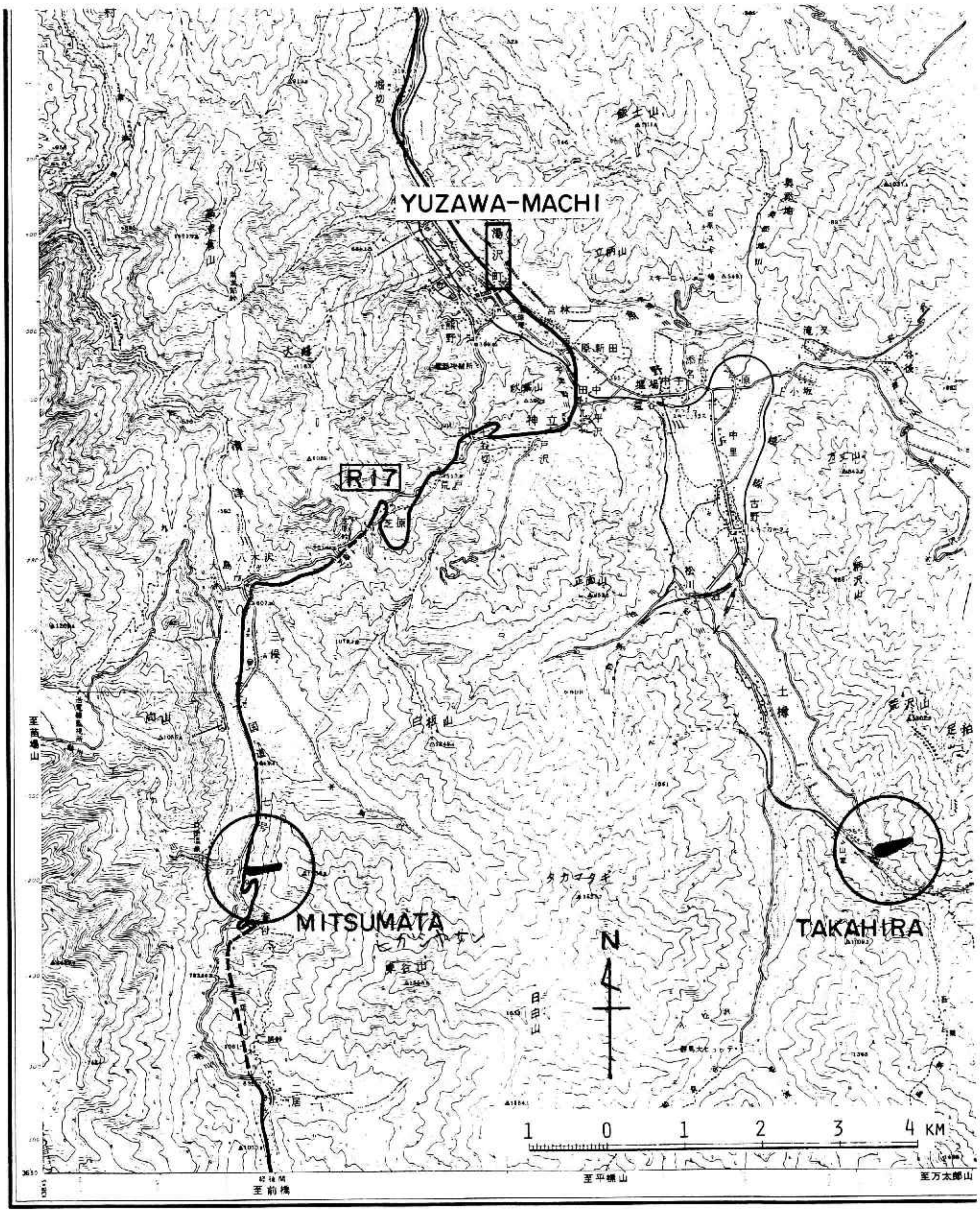
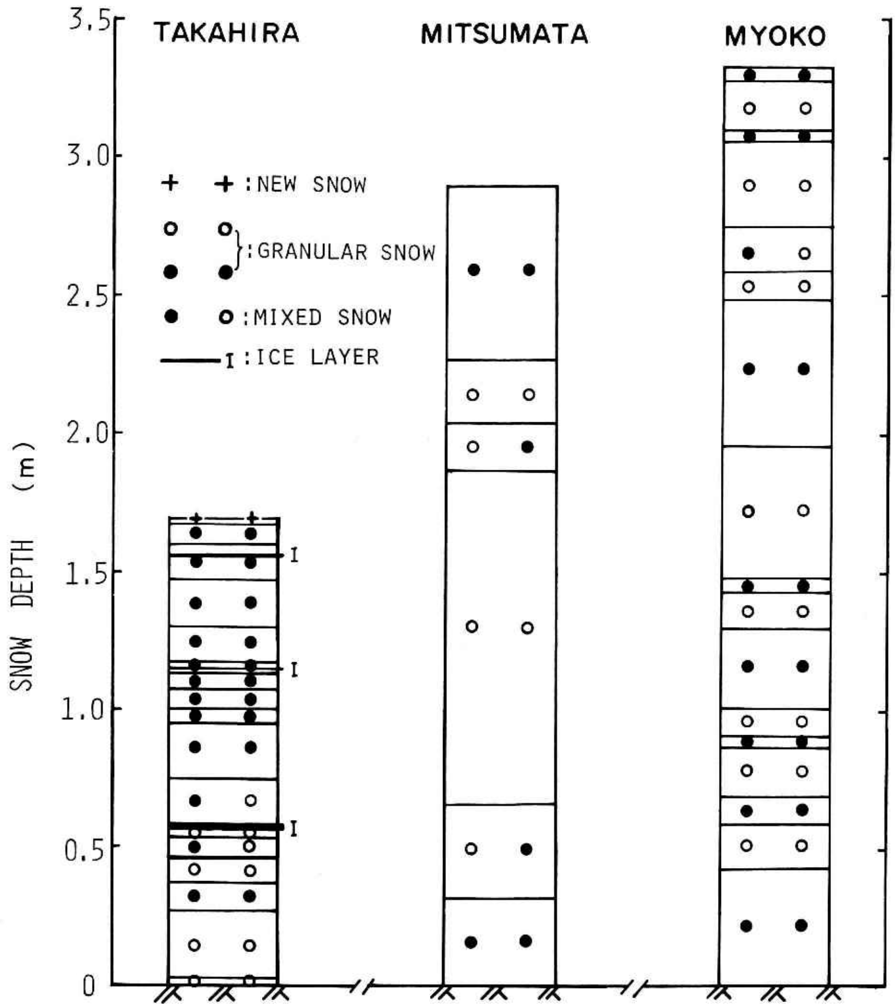


Fig. 3: Proximity of avalanche paths Takahira and Mitsumata to railroad and highway arterials in central Japan

beyond two barriers in the path at elevation 615 m. Mean density of the snow was 389 $kg{\cdot}m^{-3}$. Total runout time on the average 34° slope was 38.5 sec. Snow pit and kinematical leading edge position-time data are published for this experiment, numbered 12b, by Shoda, 1965. The leading edge position versus time plot of this avalanche is shown in Figure 6. The solid lines connect reported data points. The dashed line shows the region where the leading edge was apparently shrouded by the powder cloud produced by the



DATE	6 MAR.1961	17 MAR.1967	18 FEB.1966
AIR TEMP. (TIME)	1°C (13:35)	6°C (12:00)	4.3°C (11:00)
SNOW TEMP.	0°C	0°C	0°C
SNOW DENSITY	389 kg m^{-3}	414 kg m^{-3}	376 kg m^{-3}
WETNESS	(WET)	WET	MOIST OR WET

Fig. 4: Pit data for the three avalanche paths

explosion, and no data points are shown in the original reporting. In numerical modeling this profile the three computer codes matched the near-steady runout beyond 200 m along the path, using constant parameter values for the different coefficients of each code. This is what will be termed the "high speed" part of the leading edge trajectory. However, in the

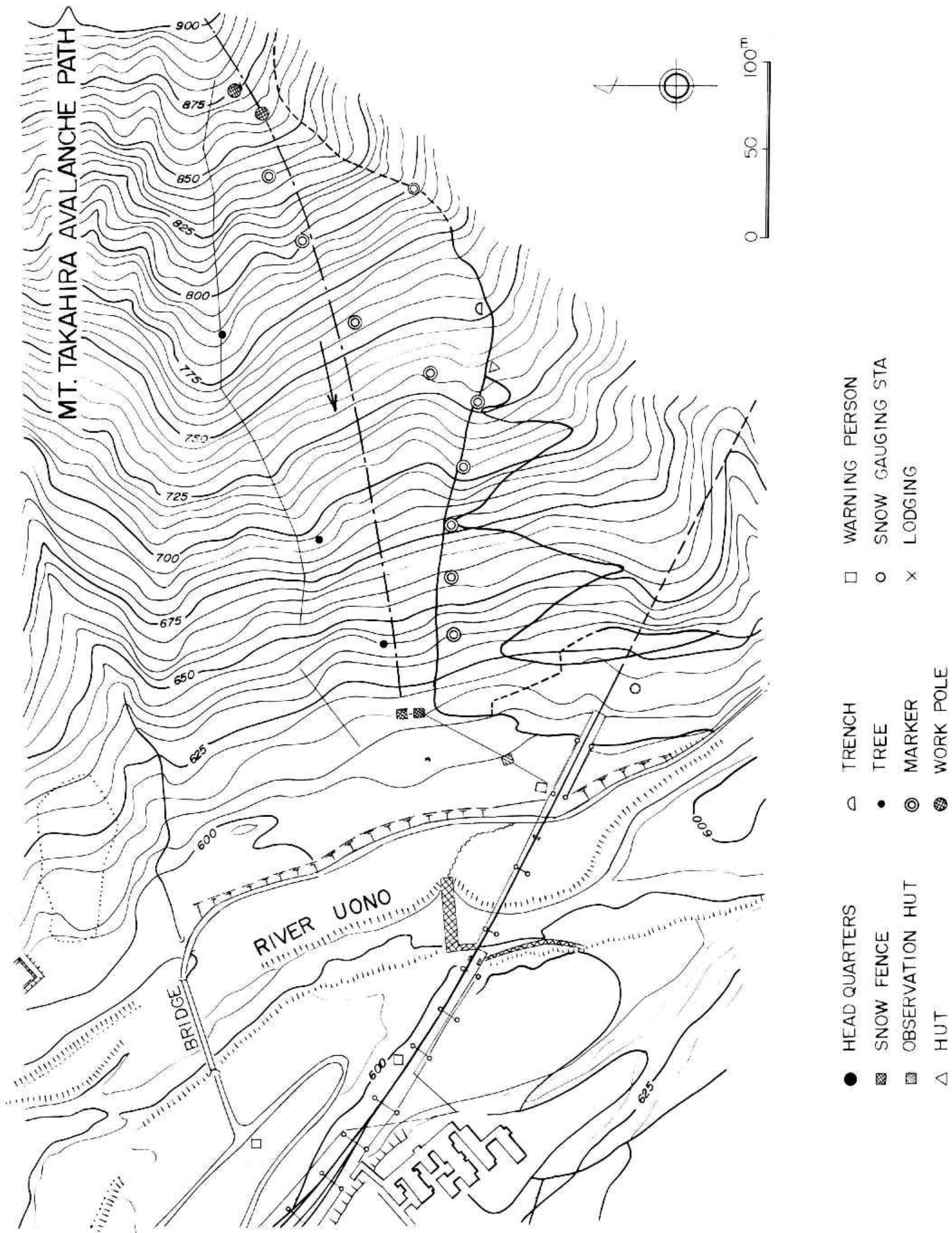


Fig. 5: Mt. Takahira avalanche path

range below about 170 m the high speed solutions deviate from the experimental curve if the parameter values are kept constant.

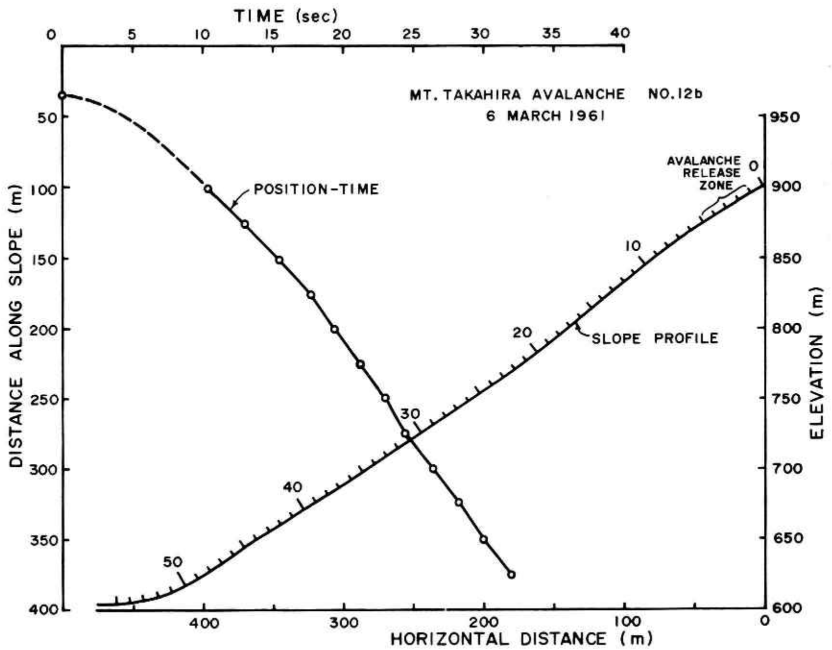


Fig. 6: Slope-profile and position-time plots of Mt. Takahira avalanche No. 12b, 6 March 1961

For all programs, the centerline profile of the avalanche path (Figure 5) was represented by 55 segments, each 10 m long. Snow of nominal depth 1.3 m was placed in segments 1 through 4, which was the specified starting zone of avalanche No. 12b. Using program BIAV, a high speed solution that matched the experimental curve from 170 m onward, was obtained with viscosity set at $\nu = 0.30\ m^2 s^{-1}$. This value of viscosity is indicative of wet snow, as a value typical of a dry snow avalanche is $\nu = 0.23\ m^2 s^{-1}$. As the high speed solution is plotted back toward the starting zone of the avalanche, the mismatch between the experimental and computer results is apparent. This is shown in Figure 7 by the computer curve labeled $\nu = 0.30\ m^2 s^{-1}$, compared to the experimental curve, and shows a time difference of approximately 7 seconds in extrapolating the curves back to the point of motion initiation.

With program BIAV the viscosity is the only parameter that can be varied along the avalanche path. The question is what increase in viscosity over what span of segments is needed to conform the computer solution to the experimental curve. It was determined that by increasing the viscosity to $\nu = 0.73\ m^2 s^{-1}$ in the first 6 segments along the path that a close fit was obtained between the computer and experimental data. The six cells in which viscosity was increased are the four in which the slab is initially released, plus two cells into which the avalanche flows after release. Thus, the correction extends only two cells ahead of the release zone. It was determined that if fewer or more cells than six were used, correspondence decreased. The modified computer curve, labeled $\nu = 0.73\ m^2 s^{-1}$ (6 segments) in Figure 7, conforms well to the experimental curve over the entire trajectory of the avalanche. Since experimental data is not given on final slowdown and

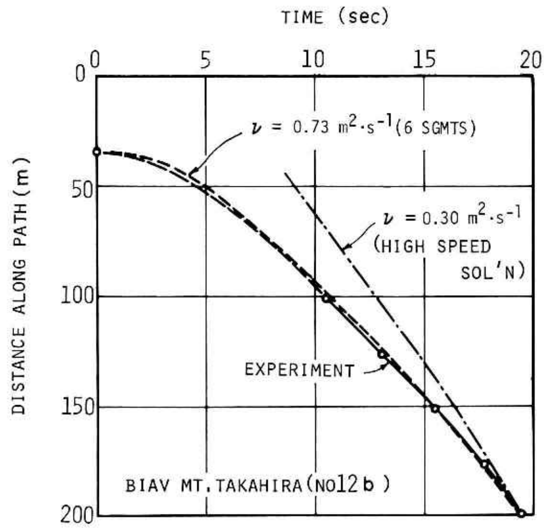


Fig. 7: Comparison between BIAV computed and experimental startup of avalanche No. 12b, Mt. Takahira

stop of the avalanche, the slowdown dynamics of the avalanche was not evaluated.

Programs BIEQ and ACEL, both based upon equations of uniform flow dynamics, and both having two dissipation coefficients, give virtually identical results when applied to the Mt. Takahira avalanche 12b. With these programs flow initiates differently than with program BIAV. In program BIAV, stationary snow to a depth of 1.3 m is placed in segments 1 through 4, and the subsequent motion of this snow determined as motion advances into segment 5 and beyond. Thus, the dissipation assumed in segments 1 through 4 influences the startup motion. With programs BIEQ and ACEL, motion is initiated by placement of snow at the start of segment 5, with zero velocity. Thus, no account is taken of conditions in segments 1 through 4 as motion advances. With program BIEQ, the high speed part of the flow was defined by assigning $\mu_0 = 0.055$ and $\nu_0 = 0.055\ m^2$ for the friction and viscosity coefficients, respectively (Figure 8). In the case of program ACEL the coefficients were $\mu = 0.05$ and $M/D = 35$ m, in order to match the high speed part of the motion (Figure 9). With both programs the time mis-match at motion initiation is about 6 seconds. Of the two coefficients in these programs, friction was initially deemed the more logical parameter to increase in attempting to match the motion during startup. For both programs the correction needed extended from segment 5 through 16, and involved increases in friction by factors of 5.5 and 7.0 to $\mu_0 = 0.30$ and $\mu = 0.35$ for programs BIEQ and ACEL, respectively.

If instead of friction the viscosity coefficient is increased in program BIEQ, the startup is matched with $\nu = 0.15\ m^2$ (compared to the high speed value $\nu_0 = 0.055\ m^2$) when the increased value is specified in cells 5 through 11.

5. Discussion: Mt. Takahira Analysis

Results obtained using three current avalanche runout computer programs indicate that the mechanics of motion initiation or startup of snow avalanches is apparently different from that of later high speed motion. Viewed physically, during startup the motion is

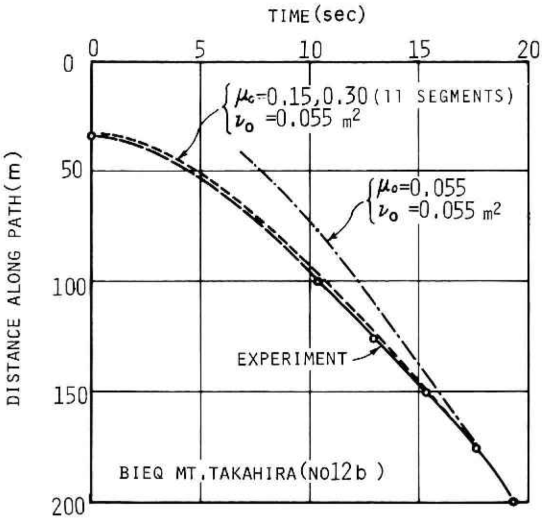


Fig. 8: Comparison between BIEQ computed and experimental startup of avalanche No. 12b, Mt. Takahira

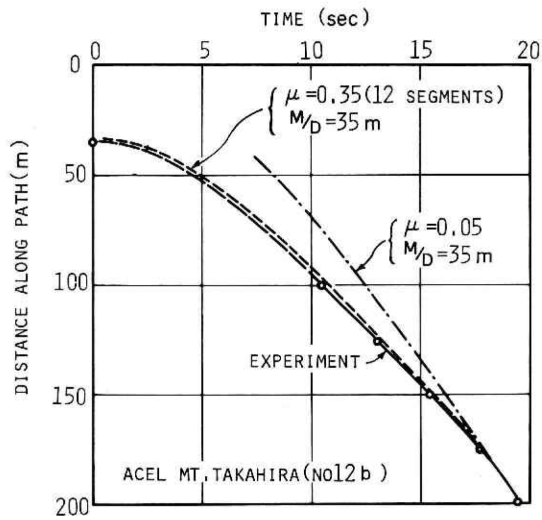


Fig. 9: Comparison between ACEL computed and experimental startup of avalanche No. 12b, Mt. Takahira

primarily sliding, until the large blocks of snow rotate and breakup, and for granularized snow to accumulate at the lower boundary of movement. In the case of artificial release by explosives, as considered herein, initial fragmentation and block breakup is likely to occur faster than with natural releases. Thus, the startup zone in natural avalanche releases may be longer than for these artificial releases. Using program BIAV, based upon transient fluid dynamics, increasing the viscosity by a factor of 2.4 in four segments in the avalanche release zone and in two 10 m segments ahead of the release zone was needed in order for the computer results to match the experimental data. With this program, with only one parameter that can be varied, increasing the viscosity decreases internal mixing and makes the snow more resistant to change in motion.

With two other programs, BIEQ and ACEL, that use hydrodynamic equations to represent uniform flow, the startup zone correction was more extensive, and the parameter changes greater than for BIAV. In these programs, if the friction coefficient is increased in the startup zone, a total of twelve 10 m segments ahead of the release zone are needed, with the coefficient increased by factors of 5.5 and 7.0. What resulted from this were friction coefficients in the range 0.3 to 0.35, which falls in the range of reported friction coefficients for sliding snow blocks (Inaho, 1941). In the high speed range the friction coefficients were $\mu_0 = 0.055$ and $\mu = 0.05$, values lower than what is usually associated with avalanche motion. Note, that these findings can only be interpreted as trends, since explicit experimental values for friction are not known for avalanche flow, and values obtained from these computer studies are not physically referenced. However, we note that with the snow-pack released by explosives, with attendant greater fragmentation than with a smooth natural release, that viscous flow should develop rapidly. Thus, the short viscous correction of program BIAV is considered in closer agreement with physical processes than the relatively extensive frictional corrections that were needed with programs BIEQ and ACEL.

If viscosity is changed instead of friction in program BIEQ, the coefficient must be increased by a factor of 2.7, and must extend for seven 10 m segments ahead of the release zone. The trend shown by these results is that viscous correction for startup is of smaller magnitude and extends over shorter distances than corresponding friction correction. That it takes 120 m of increased friction at roughly 6 times the high speed value to match the Mt. Takahira startup is not as intuitively reasonable as what has been found for viscosity. Thus, these results tend to confirm the viscous fluid character of avalanching snow.

In matching the high speed part of the displacement-time plots from the computer to the experimental results a 6 or 7 second time difference was noted. With the 38.5 second total runout time of the Mt. Takahira avalanche, the error is significant at 18%. However, if the programs are applied to much longer running avalanches, then the error associated with startup is negligible.

6. Mitsumata Slope Avalanche Path

The Mitsumata slope, located on Mt. Higashiya is 8 km west of Mt. Takahira, and is 58 km from the Sea of Japan. The slope of this avalanche path extends from 1280 m to 700 m in elevation. However, the experimental avalanches were released below a bench of the slope at elevation 925 m (Figure 10). On 3 March 1967 a wet snow avalanche was artificially released by explosives. The nominal 2.0 m deep snow slab of mean density 414 kgm^{-3} after release ran to the base of the average 32° slope. Data on the kinematics of the flow of this avalanche is presented in the form of leading edge position versus time drawn relative to the slope (National Highway, 1971). From this data, position versus time of the leading edge of the avalanche was constructed (Figure 11). The rapid variations obtained in this curve are not substantiated by corresponding topographic irregularities, and so are attributed to error associated with interpolation of the leading edge-time plot data. Since contour lines were not superimposed upon the data plots straight line approximations were used, which may have introduced significant error. Also, as the avalanche intercepted the snow shed, and wall (Figure 11) the leading edge shape changed, which

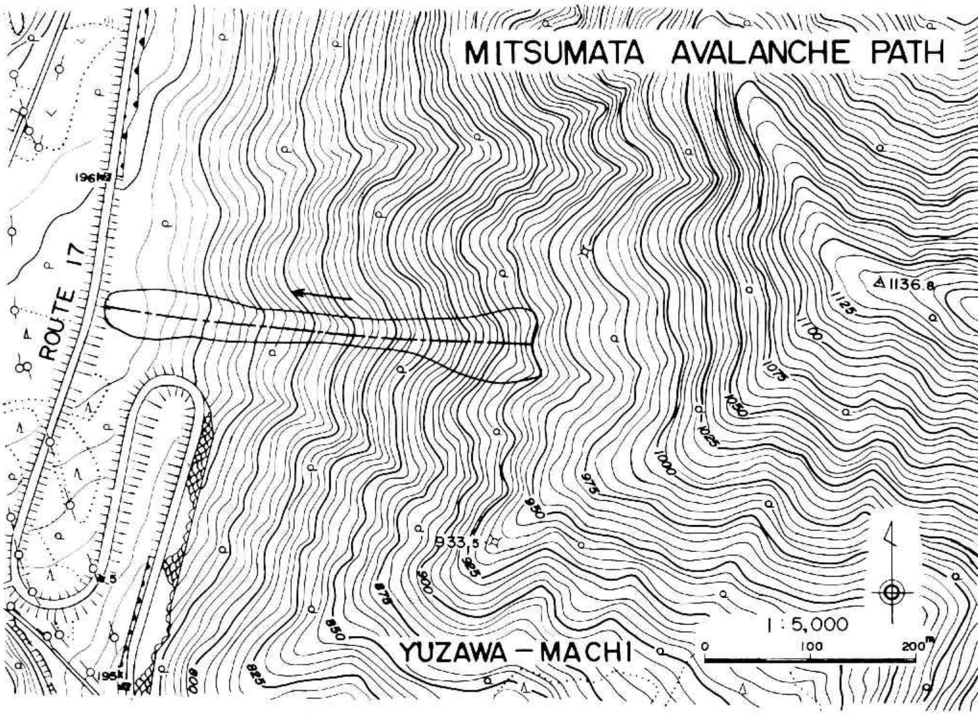


Fig. 10: Mitsumata avalanche path

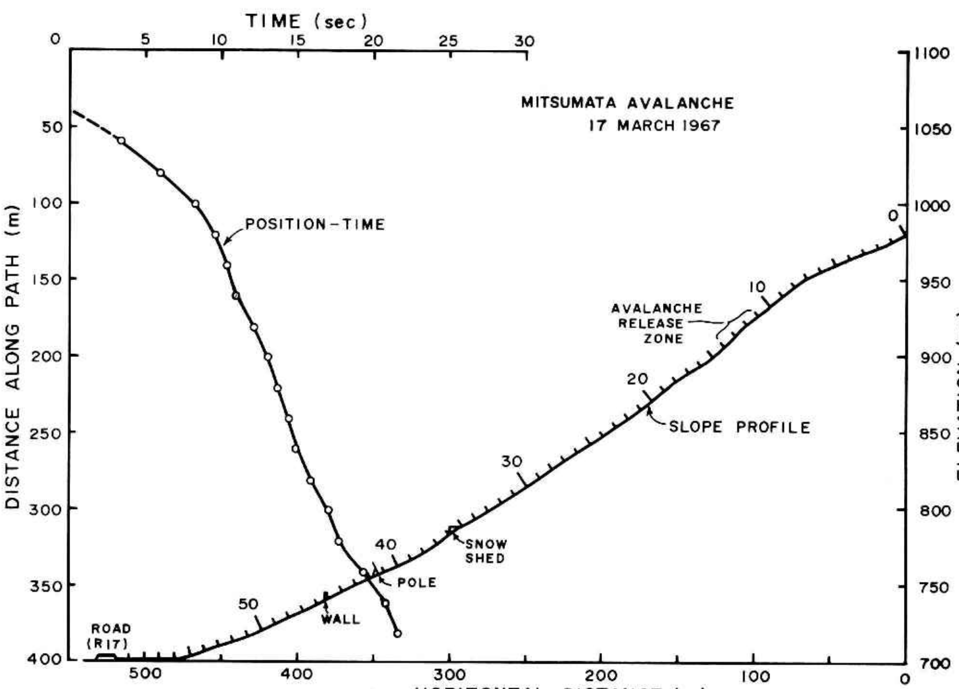


Fig. 11: Slope-profile and position-time plots of Mitsumata slope avalanche of 3 March 1967

required additional interpolation in order to obtain the position-time plot of Figure 11, which is not intended to show the local slow-down due to obstacles. As with Mt. Takahira, the actual start of the Mitsumata slope avalanche was shrouded by a powder cloud, so a portion of the position-time plot is shown dashed.

Startup acceleration of the Mitsumata slope avalanche is greater than that of Mt. Takahira covering 90 m compared to 60 m in the first 10 seconds of motion. Also the startup zone is shorter than with Mt. Takahira, so that if the highspeed computer solutions are extrapolated back to the point of release the time difference is less than 5 seconds, compared to 6 or more for Mt. Takahira (Figure 12). One complication arises, that in the position-time plot, constructed from the pictorial leading edge-time data, a near constant slope region is obtained between 50 and 100 m along the path (Figure 12). Apparently this is an interpolation error, as the coefficients in programs BIEQ and ACEL could not be changed sufficiently to produce kinematic correspondence in this region. This means that the slope profile in this region is not compatible with the estimated position-time profile. Using program BIAV a correspondence is this region can be obtained, however, the correction needed is more extensive than that for Mt. Takahira. So with the

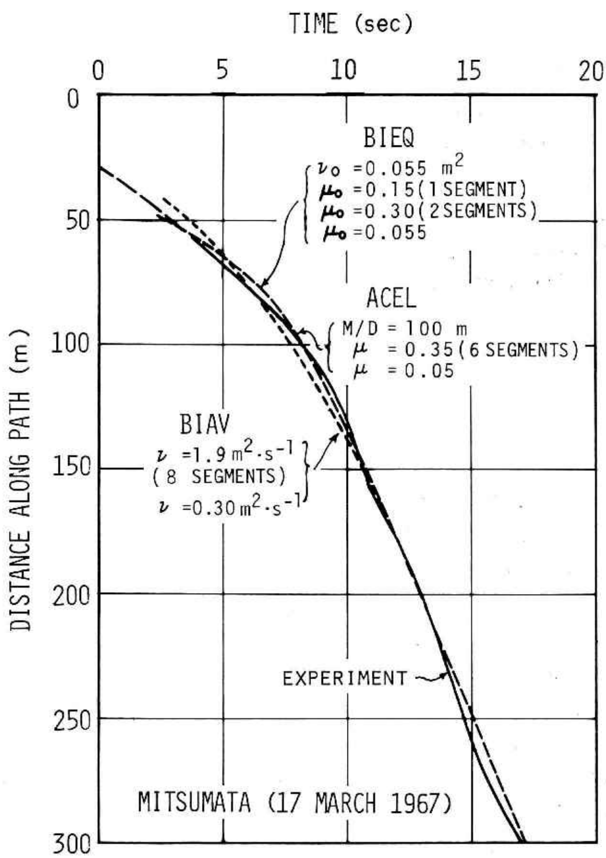


Fig. 12: Comparison between computed and experimental startup of Mitsumata slope avalanche, 17 March 1967

programs a correction was saught that resulted in a position-time trajectory that intercepts the release point, but do not necessarily conform to the position-time plot at other points. For program BIEQ, the viscosity was kept constant at $\nu_0 = 0.055\ m^2$, the same value as used with Mt. Takahira. The friction was increased to $\mu_0 = 0.15$ in the first segment and to $\mu_0 = 0.30$ in two additional 10 m segments ahead of the release point. For the remaining 41 segments the friction was set at $\mu_0 = 0.055$, also the same as for Mt. Takahira. Using program ACEL, the viscosity coefficient was increased, because of the deeper flow in this case, to M/D = 100 m over the entire path. Then to correct for startup, the friction coefficient was increased to $\mu = 0.35$ for 6 segments ahead of the release. For the remainder of the runout, friction was set at $\mu = 0.05$, the same as for Mt. Takahira.

Program BIAV, which showed a strong transient perturbation over the first 3 segments of motion, settled into a near correspondence with the experimentally based position-time trajectory of the leading edge if the viscosity was increased by a factor of 6 to $\nu = 1.9\ m^2 s^{-1}$ for 8 segments, 5 of which were ahead of the release. Following this, $\nu = 0.30\ m^2 s^{-1}$ gave a high speed fit, the same value as used with Mt. Takahira.

7. Discussion: Mitsumata Slope Analysis

Apart from the apparent non-correspondence between the slope profile and the experimental position-time trajectory of the data for the Mitsumata slope, the computer results show a consistency between the two avalanche paths (Mitsumata and Takahira). The Mitsumata slope avalanche starts faster, so the coefficient corrections to the avalanche programs extend over a smaller number of segments in the startup region. For the approximate corrections obtained with programs BIEQ and ACEL, the increase in values of the friction coefficients are the same as those for Mt. Takahira. Programs BIEQ and BIAV, which have internal equation adjustments for different avalanche depths, both used the same high speed coefficient values to model the high speed kinematics. Program ACEL which has no internal correction for different avalanche depths required a factor of 3 increase in the value of M/D to model the high speed kinematics of the 2.0 m deep Mitsumata slope avalanche compared to the 1.3 m deep avalanche of Mt. Takahira.

8. Mt. Myoko Avalanche Path

The Mt. Myoko avalanche path, a southeasterly facing slope, is located 56 km due west of the Mitsumata test slope. The Myoko test slope extends from an elevation of 1100 m down to 800 m, and located only 23 km from the Sea of Japan, is subject to strong coastal conditions on the basis of prevailing winds from the west. On 18 February 1966 a wet snow avalanche of 2.0 m average depth was released by explosives, and traversed the dashed line path on the contour map of Figure 13. Mean density of the snow was 376 $kg \cdot m^{-3}$, and the avalanche ran to the base of the average 34° slope. Position versus time of the avalanche front was measured by three techniques, namely, by a series of stereographic still photographs, by stop watch measurements, and by 16 mm movie footage (KAWASAKI, 1966). Because of stated inaccuracy of the movie film method, the displacement-time plot was taken as the average of the measurements by the other two techniques, which were in close correspondence. The displacement-time plot and the slope profile used in the computer modeling are shown in Figure 14.

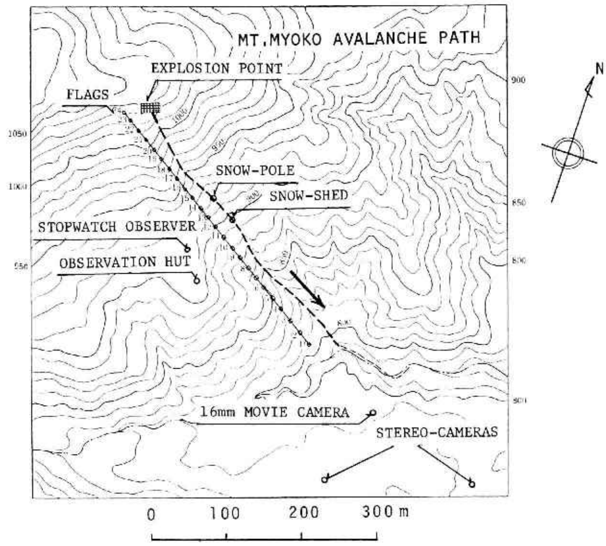


Fig. 13: Mt. Myoko contour map and avalanche path

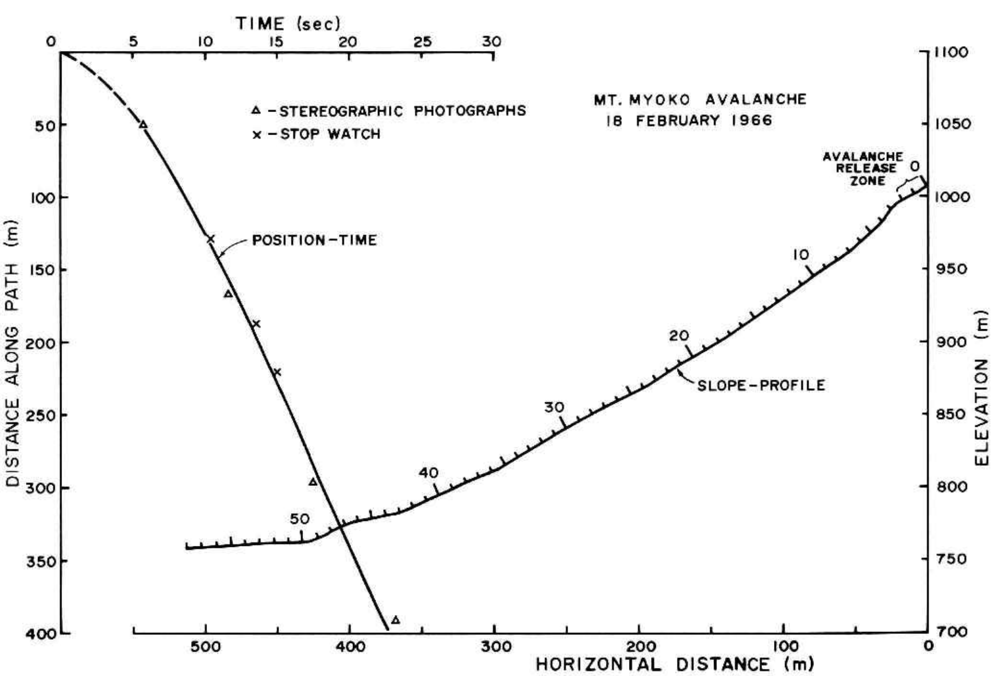


Fig. 14: Slope-profile and position-time plots of Mt. Myoko avalanche of 18 February 1966

Of the three avalanches, the Mt. Myoko avalanche has the greatest startup acceleration, covering 120 m along the path in 10 seconds after release. This is due in part to a near cliff geometry in the profile 4 segments along the path (Figure 14). This rapid acceleration results in only a 3 second time difference between the actual startup and the start predicted from the high speed trajectory analysis. With all programs, small increases in the high speed motion resistive parameters were needed with Mt. Myoko, apparently because of increased water content of this avalanche. With program BIEQ the high speed friction and viscosity coefficients were increased 15%. With program ACEL friction was increased 9%, and with program BIAV viscosity was increased 17%.

In adjusting to match startup, friction was increased to 0.15, 0.30, 0.30 and 0.30 in 4 segments then dropped to 0.045 for the high speed portion of the runout using program BIEQ (Figure 15). In the case of the Mitsumata slope a similar correction was needed, but extended over only 3 segments of the path. With program ACEL the low speed correction to friction amounted to $\mu = 0.35$ for six segments decreased to $\mu = 0.055$ for the remaining runout. The six segment correction is identical to that of the Mitsumata slope. With program BIAV, a viscosity of $\nu = 1.7\ m^2 s^{-1}$ was needed over 6 segments, 4 of which were ahead of the avalanche release zone (which was 2 segments for the Mt. Myoko release). The corresponding results for the Mitsumata slope involved a value of $\nu = 1.9\ m^2$ for 8 segments, of which 5 were ahead of the release zone.

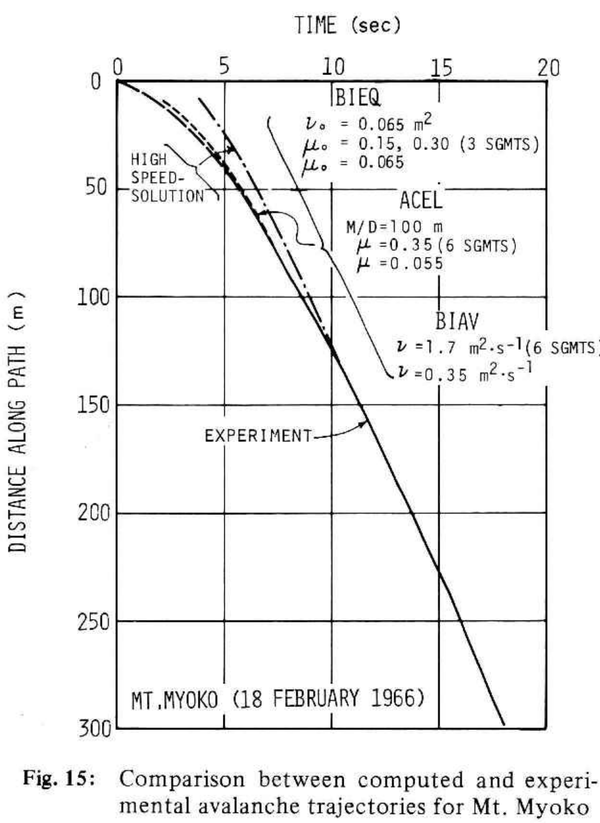


Fig. 15: Comparison between computed and experimental avalanche trajectories for Mt. Myoko

9. Discussion: Mt. Myoko Analysis

The time difference between the high speed solution and actual release is only 3 seconds for Mt. Myoko, compared to 5 seconds for the Mitsumata slope. However, correction to the avalanche programs in order to match the startup trajectory is of the same order for Mt. Myoko as for the Mitsumata slope. The reason for this is apparently in the fact that in only 80 m the Mitsumata experimental and computer trajectories come intc coincidence, whereas for Mt. Myoko the corresponding distance is 120 m. For Mt. Takahira the distance is roughly 150 m, with some variation between programs.

10. Conclusions

Listed in Table 1 are the coefficients used in order to model the startup transients of the three avalanches considered. Looking at the results of programs BIEQ and ACEL, the two programs based on equations of uniform flow hydrodynamics, the question comes up as to why the extended correction is needed for the Mt. Takahira path, while considerably less extensive corrections are needed for the other two avalanche paths. In considering trends that might attribute to the difference, the variation in slope angle of segments in each starting zone was considered. The average variation in slope angles for each avalanche path is shown in Figure 16. Both Myoko and Mitsumata have similar characteristics of initial large slopes subsequently reducing to milder slopes, in what might be termed concave starting zones. However, Takahira shows the opposite trend of slope angles increas-

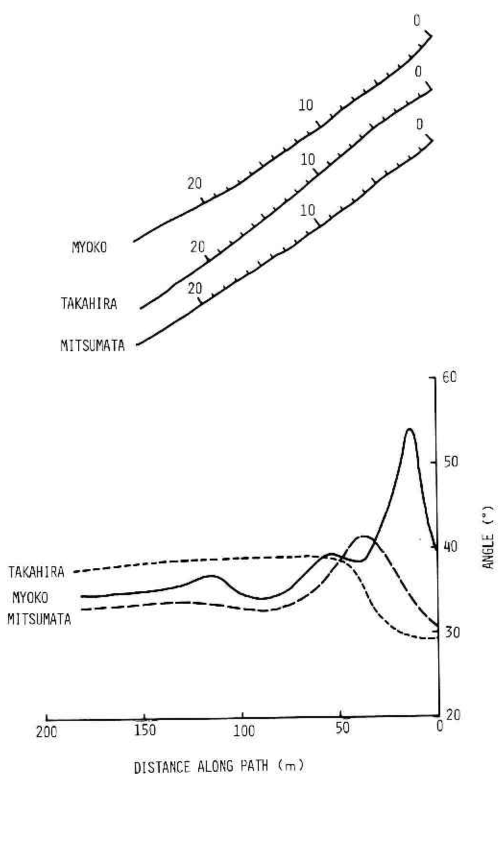
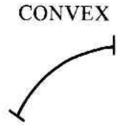
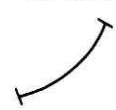
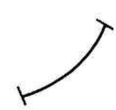


Fig. 16: Average slope variation versus distance along paths of three avalanche starting zones

TABLE 1: Summary of avalanche properties and computer program parameterization to model start-up transients of avalanche flow

Program \ Avalanche Place			Mt. Takahira	Slope Mitsumata	Mt. Myoko
BIAV	Avalanche Depth		1.3 m	2 m × 2, 1.5 m, 1 m	2.0 m
BIAV	Avalanche Cell		10 m × 4	10 m × 4	10 m × 2
BIAV	ν $(m^2 \cdot s^{-1})$	Start	0.73 (6 SEG.)	1.9 (8 SEG.)	1.7 (6 SEG.)
BIAV	ν $(m^2 \cdot s^{-1})$	High Speed	0.30	0.30	0.35
BIAV	ν $(m^2 \cdot s^{-1})$	Factor	2.4	5.7	4.9
ACEL	Avalanche Depth		–	–	–
ACEL	Avalanche Cell		10 m × 4	10 m × 4	10 m × 2
ACEL	μ	Start	0.35 (12 SEG.A.)	0.35 (6 SEG.A.)	0.35 (6 SEG.A.)
ACEL	μ	High Speed	0.05	0.05	0.055
ACEL	μ	Factor	7.0	7.0	6.4
ACEL	M/D (m)	Start / High Speed	35	100	100
BIEQ	Avalanche Depth		1.3	2.0	2.0
BIEQ	Avalanche Cell		10 m × 4	10 m × 4	10 m × 2
BIEQ	μ_0	Start	0.15 (1 SEG.A.) 0.30 (11 SEG.A.)	0.15 (1 SEG.A.) 0.30 (2 SEG.A.)	0.15 (1 SEG.A.) 0.30 (3 SEG.A.)
BIEQ	μ_0	High Speed	0.055	0.055	0.065
BIEQ	μ_0	Factor	5.5	5.5	4.6
BIEQ	ν_0 (m^2)	Start / High Speed	0.055	0.055	0.065
Ave. Slope of Starting Zone			36.9°	36.0°	39.2°
Starting Zone Length			150 m	80 m	120 m
Starting Zone Shape			CONVEX 	CONCAVE 	CONCAVE 

ing, staying large, then finally reducing to smaller values, in what can be termed a convex distribution relative to those of Myoko and Mitsumata. And it is this difference in slope profile that is likely to contribute to the differences in the number of segments wherein parameters were increased in order to match the startup transient. In the case of a concave slope, material accelerates fast on the initial steep slopes, then moderates as the slope angles decrease. So if retardation is supplied in the steep slope region, then this slowdown is reinforced by the follow-on reduced slope. This accounts for the relatively short corrections that were needed for avalanches Myoko and Mitsumata. In the case of a convex slope, initial resistance is not reinforced by follow-on slope changes, rather, in fact, the continuing increase in slope tends to counter the flow resistance. Under these conditions it is reasonable to expect the startup correction to extend over a larger number of segments as was found with Takahira. These findings explain the differences noted with programs ACEL and BIEQ for the different avalanche paths, but program BIAV shows results that indicate a more uniform correction for the three cases. In fact, for Takahira the correction may be interpreted as less than for Mitsumata and Myoko. However, it must be remembered that program BIAV is a transient flow code in which the depth of flow is variable. Thus, on a convex path the flow depth would decrease, while on a concave path the opposite would occur. Since flow depth is the most sensitive parameter associated with avalanche flow (Lang, Dawson, Martinelli, 1979), small decreases in the case of Takahira and small increases with Mitsumata and Myoko, may have moderated the strong differences obtained with the other codes. Thus, the shape of the starting zone apparently has significant effect on the startup kinematics depending upon the type of computer program used to analyze the transient. Apparently, with program BIAV, the viscosity increment is roughly proportional to the initial depth of flow. With Takahira the viscosity is increased by a factor of 2.4 for a 1.3 m deep flow, while for the other avalanches with 2.0 m deep flows, the viscosity is increased by factors of 5.7 and 4.9. Thus a rough doubling in flow depth requires a rough doubling in initial viscosity.

The other basic result noted from the Table 1 data is that values for the Coulomb or dry type friction used in programs BIEQ and ACEL are well below previous minimums established in other empirical parameter investigations. However, the trend noted in this study of decreased importance of dry friction in avalanche flow, as viscous properties of flowing snow are more accurately represented, that is low-stress locking, is consistent with fluid mechanic properties of flowing materials, in general. That is, that the viscous property, which is the basic dissipative mechanism in fluids, needs to be considered in greater detail in application to snow avalanche flow.

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雪崩発生動力学のコンピューター的研究

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要　旨

雪崩の運動の記述を大別すれば二つになる．一つは非圧縮性流動を表現するナビエ・ストークスの方程式を用いるもの，もう一つは質点運動論的に表現するヴェルミーの運動方程式によるものである．前者には乾燥摩擦抵抗項は入っていない．後者には乾燥摩擦抵抗項と，速度の二乗に比例する動粘性抵抗項の二つが入っている．

この報告の新しい点は次の通りである．

① 従来使用されてきた方程式中の係数は，人工雪崩等の野外での実験値を基に決められたものではなかったが，ここでは，荘田幹夫達が過去20年間にわたって日本の三地点で行なった人工雪崩実験の実測値との対比から係数が求められたこと．

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② 日本の湿雪雪崩の運動を上記の方程式にあてはめて，これらの方程式の使用可能性を確認し，かつその範囲を広めたこと．
③ 三つの斜面での雪崩を三つの方程式（速度の二乗に比例する動粘性係数の項が入った式が二つある）で表現した結果，斜面の形（凹か凸か）により斜面プロファイル中の摩擦抵抗項を増やさねばならぬこと．すなわち，凸斜面の場合には，重力による加速性が増す分だけ増加させねばならないこと，凹斜面では凸斜面より少なくてすむこと，などである．

なお，この報告書は，ラング教授が昭和58年度科学技術庁外国人研究者として当新庄支所に滞在中になされた仕事の一部である．ラング教授と国立防災科学技術センターとの係わりの詳細については，当センター研究速報第59号の序に書いてある．