Twenty-five Years of Snow and Avalanche Research at NGI: Geotechnique Contributions

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ABSTRACT: In this paper, I wish to review the far reaching contributions from snow and avalanche research at NGI over the last 25 years. My review is based on my own association with the research at NGI (24 years) as well as the implications of the research on a world scale. The paper is confined to those applications which have important geotechnique applications. Therefore, the important work in avalanche forecasting and other practical research results such as natural hazards mapping are not discussed here. The topics include: forces on structures in deep snowcovers, runout distances using terrain parameters, slushflow research and avalanche dynamics and impact pressures.

FORCES ON STRUCTURES IN DEEP SNOWCOVERS

Work on specifying forces on structures in deep snowcovers began in 1976 in cooperation with the Norwegian Water Resources and Energy Administration (NVE). Experimental work was initiated by measuring strains on three constructions placed on a mountainside near the NGI high mountain station at Grasdalen, Western Norway. The strain measurements were made by vibrating wire strain-gauges on the three types of structures. The three types of structures were: 1. three sections (measurements on the centre section) of an avalanche defence structure to provide approximately plane-strain conditions for comparison with analytical models and formulas in the Swiss Guidelines; 2. a steel single pole to simulate forces on ski lift towers and trees; and 3. a section of a powerline mast to simulate forces on NVE's powerlines through the mountains (data which are not yet analyzed). The measurements were supplemented by snow profiles at the site to get depth, density estimates and snow gliding measurements. The latter showed that there was negligible gliding at the sites of the experiments.

Results: avalanche defence structure

Data were collected at the centre section of three sections of the avalanche defence structure for many years. This body of data gave important information about the forces expected for the analytically simple plane strain problem which, in combination with earlier results in Switzerland, enabled checking with the formulas for snow pressure in the Swiss Guidelines for Avalanche Defence (1990).

In addition to the experimental work, analytical and numerical formulations were made with respect to the plane-strain problem. These were based on the assumption that the snow could be modeled as a linear, viscous, compressible fluid with neglect of the static pressure term (Salm, 1967). For the plane-strain problem, the results depend only on the ratio of shear to bulk viscosity (or viscous analog of Poisson's ratio) for which reasonable limits are known theoretically for alpine snow (e.g. Mellor, 1968). Principal results of comparison of the data (both Swiss and Norwegian) with the theories are as follows:

i. A linear, compressible viscous fluid can adequately represent alpine snow for the plane strain problem for reasonable limits of the viscous analog of Poisson' ratio (0 to 0.4) for the plane strain problem. However, if problems with higher forces are encountered such as at the extremes instead of the centre of the structure, non-linear modelling **may** be needed.

ii. When the plane-strain problem is formulated from continuum mechanics, it is possible to solve it analytically (checked with finite element calculations) by one-dimensionalizing the problem including gliding. This formulation showed that creep and glide do not couple into the problem as in the Swiss Guidelines (creep and glide factors) and therefore, it is believed that the analytical formulae in the Swiss Guidelines are not correct. Further, the Swiss Guidelines neglect the "static" pressure term which arises from body force perpendicular to the ground. This force is a real force which is easy to calculate for the linear problem and it should be included.

iii. The problem becomes fully two dimensional if there is no slip parallel to the structure and no simple analytical formation is available as in ii where the assumption of free slip makes the problem one-dimensional. Approximate analytical expressions were developed for the case where slip takes place parallel to the structure by a combination of numerical and analytical results.

Results: single poles

Experimental data (Larsen, Laugesen and Kristensen 1989; Larsen and Laugesen, 1991) were collected over many years in order to understand the forces on a single pole of finite diameter erected perpendicular to the slope. The data collection represents the most comprehensive yet published and, therefore, they are extremely important. Theoretically, the problem is fully three dimensional with complications because snow separates from the pole on the downstream side. Further, in this case the forces are much higher than the plane-strain wall case and it is possible that non-linear affects enter. The results also clearly depend on the diameter of the pole in relation to the snow depth. In this case, empirical results were obtained relating forces on the pole to snowpack properties including density, depth, hardness and temperature. The resulting relationships provide simple formulations to estimate forces and moments for the case at hand: poles with diameter similar to the one used (0.42 m). In 1983, a single pole with 0.22 m diameter was erected in order to study the effects of diameter. The results from both poles along with other information indicate that the total load on a pole increases approximately with the square root of the pole diameter.

Another very important result was measured during a winter with a deep snow-pack with snow-pack temperatures close to 0^0C. The evidence showed that regelation took place around the pole due to high pressures and warm temperatures resulting in an encrustation of snow and ice around the pole to increase its effective diameter by a factor of at least two. This resulted in the maximum design forces for the structure: considerably higher than situations without regelation taking place. This result could not have been extrapolated from data for normal winters without regelation.

Summary: forces on structures in deep snowcovers

The work concerning creep forces on structures in deep snowcovers represents a comprehensive set of measurements both for the plane-strain problem of forces at the centre of an avalanche defence structure and for single poles which mimic structures such as ski lift towers. Simple analytical formulae have been developed to replace the formalism in the Swiss Guidelines for Avalanche Defence for the plane-strain problem and these formulae have been checked against measurements in Grasdalen and Switzerland. The analysis shows that a two parameter linear viscous fluid is adequate for the plane-strain problem.

From the data on single poles analytical expressions have been developed to enable estimation of the maximum moment at the bottom (ground interface) of the pole depending only on density and snowdepth, H^3. The data also show that the optimum conditions to achieve maximum pressures on the poles occur under special conditions when the snow-pack is deep and warm, possibly with regelation forming a solid coat around the upslope portion of the pole to increase the effective diameter. In this case, the pressures are deemed to be much higher than the plane-strain configuration and are possibly beyond the range of a linear, viscous model.

RUNOUT DISTANCES USING TERRAIN PARAMETERS

There are two general approaches to calculating runout distances of avalanches: 1. selecting and using friction coefficients in an avalanche dynamics model and 2. empirical calculations using terrain parameters. Method 1 is the oldest one and it was pioneered by Voellmy (1955). There are severe disadvantages to method 1 at this point in history. Namely, a mathematical characterization of friction parameters of flowing snow in interaction with terrain roughness obstacles is not yet available and such would be exceedingly difficult to achieve. Dynamics models are necessary to calculate expected impact forces on structures and facilities exposed to dynamic avalanche loads but their suitability for calculation of runout distances is not easily demonstrable in spite of the fact that many do it. If this is true, which I believe it is, then we are left only with method 2.

The reason method 1 "works" in practice is that, in reality, method 2 is being used de facto: by specifying dynamics friction coefficients, the runout distance is specified.

Method 2 began, in earnest with the landmark paper by Lied and Bakkehøi, 1980. They defined the extreme runout distance from the historical record of a set of extreme runout distances (return period of order 100 years) measured in a mountain range by a least squares regression of terrain angles and path parameters. The results was an empirical prediction of extreme runout for the terrain in question formulated so that uncertainty and errors could be addressed in standard statistical terms. The concepts in the original paper have since been extended to other data sets and a host of statistical models have been developed to exploit the key idea in the model. Modellers in Spain, France, Iceland, USA, Japan, Canada and Austria have used the method in applications as well as in Norway.

The key to the method is to define the runout position from a reference position on the slope. From the work of Lied and Bakkehøi (1980) and subsequent papers it is found by world-wide experience that an excellent position is that for which the slope angle first declines to 10^0 proceeding downslope from the starting zone.
The extreme tip of the runout is demarcated by the angle α (the classical fabroschung) by siting from the tip of the runout to the start point and the reference from which runout is measured is noted by the angle β by siting from the 10^0 reference point to the start point. The method then involves a least squares regression between α (response variable) and β and other significant terrain variables which may include path length parameters and other angles. Another significant variable is δ: the angle in the runout zone defined by siting between α and β. The three angles together can be used to define a runout ratio given by $(\tan\beta - \tan\alpha)/(\tan\alpha - \tan\delta)$ which McClung and Lied (1984) showed to obey a Gumbel distribution as an alternate way to characterize extreme runout. Either the regression approach or the Gumbel approach are widely applied now in applications in many locations in the world.

The advantages of the empirical method of specifying runout are too important to dismiss: 1. use of the historical record of extreme avalanche runout to determine land-use planning in a mountain range: thereby implicitly including path terrain and climate effects; 2. specification of errors/accuracy in standard statistical terms with implicit inclusion of the statistical aspect that extreme runout data show in all mountain ranges. Field experience clearly shows that the problem of specifying runout distances does not fall within those problems amenable to deterministic methods at this stage of the research.; 3. avoidance of the use of avalanche dynamics to calculate runout which is nearly impossible due to huge uncertainties and variations with respect to properties of flowing snow interacting with terrain roughness elements. The empirical method has to be **the** method of choice for applications considering the huge uncertainties in avalanche dynamics formulations. The method pioneered by Lied and Bakkehøi (1980) is the most important advance in quantitative runout estimation in more than 40 years: the state-of-the art. The details of use of the method vary from country to country and place to place but the importance of the method and the key ideas is truly immense.

Summary: runout prediction using terrain parameters

The method first pioneered by Lied and Bakkehøi (1980) for estimation of runout distances empirically from terrain parameters is today accepted in many countries in the world including: Austria, Canada, USA, Spain, Iceland and Japan. Variations of the method including application of extreme value statistics (McClung and Lied, 1984) are popular and these have spawned a whole new generation of statistical and simulation models for estimating risk in land-use planning applications. The key to the method involves using a reference position (the β point) from which to start runout estimation and, when applied, it becomes possible to specify runout in standard statistical terms so that errors and uncertainty are quantifiable. Application of the method requires a data set from a given mountain range (McClung and Mears, 1991) before applications are attempted because the historical record of extreme avalanche occurrences varies from one mountain range to the next. The method is theoretically superior to the long standing method of selecting friction coefficients for input into an avalanche dynamics model.

SLUSHFLOW RESEARCH

Slushflows are a special type of avalanche which occur in most mountain ranges but they are particularly important in northern latitudes. The combination of mountainous terrain, northern latitudes and significant human occupation of such terrain in Norway combine to make slush flows one of the most important natural hazards in Norway. Slushflows account for approximately the same totals with respect to economic losses and damage as snow avalanches in Norway (Hestnes, 1998). This information is truly staggering and as a consequence NGI started a specific research programme on slush flows in 1983 with three objectives: identification of slushflow hazard areas, slushflow prediction and slushflow control. To date, most emphasis has been given to the first two objectives.

The research accomplishments in regard to slushflow management have been developed on the basis of long experience and measurements (meteorological and snowpack) in combination with the historical record and case histories of destructive events in Norway. Principal contributions include:

- characteristics of slushflows including snowpack properties and water supply
- geomorphology of slushflow terrain including important details about likely starting zones
- characteristics and predictors to evaluate slushflow hazard (forecasting) including relation to climate and weather patterns, characteristics and meteorological and snow predictors
- observations on the mechanism of slushflow release, flow characteristics and runout observations
- quantitative estimates of water supply (including precipitation and snow melt) to potential slushflow sites
- standardization of terminology to clarify the meaning of data sets and comparison with events from other countries

The research constitutes a far reaching, comprehensive body of information about slushflows which has validity outside Norway. The information shows that slushflows do have some general characteristics but the specifics are complex and varied particularly with respect to terrain configurations. An interesting aspect of terrain complexity is that human modification of terrain has led to slushflows (Hestnes, 1998) coincident with filling in natural drainage, blocking drainages and diversion of water into snow filled channels or outside existing drainages. In this sense, there is a commonality with certain landslide occurrences.

Research at NGI has also determined that certain snowpack characteristics are favourable to slushflow release: coarse grained snow and new snow being most prominent. Slushflows are usually thought of occurring at spring break-up but research at NGI has shown that they are most common in the early part of the winter but the larger, more destructive ones occur during late winter and spring when snowpacks are deeper.

Summary: slushflow research

The comprehensive body of data and information about slushflows and the expertise that lies within NGI about them is today unmatched in the world with respect to the breadth and depth of information. Numerous other organizations have profited from it as a result of NGI's consistent presentation of the material at symposia and conferences around the world. The mechanical properties of a layered snowpack with slush at the bottom are not well studied anywhere and forecasting requires a knowledge of geomorphic terrain factors, snowpack properties and the duration of water supply: all quantities which are difficult to know. On a world-wide basis slushflows have received much less attention than snow avalanches but the importance of the phenomenon to Norway has produced a fine body of research contributions which identify the key factors.

AVALANCHE DYNAMICS AND IMPACT PRESSURES

Avalanche dynamics is concerned with prediction of speeds along the incline and when coupled with estimates of flow densities if becomes possible to specify impact pressures for design of facilities in avalanche prone terrain. Avalanche dynamics is also necessary for the design of defences to slow or stop avalanches. Work on avalanche dynamics and associated impact pressures began at NGI almost with the inception of avalanche research in Norway with the work of Tøndel (1977). The early work involved filming avalanche events at the Ryggfonn in Grasdalen to get speed estimates for large avalanches and attempts at measuring impact forces. Beginning in 1981, a comprehensive set of instruments was added including: large impact plates, cylindrical masts, and a 15 m retaining dam structure was built in Grasdalen below Ryggfonn and impact pressures, wind speeds and tension forces on transmission line wires were measured with geophones installed along the path to enable speed estimates to be made. The historical development of the battery of instruments and the associated reports are contained within NGI reports (e.g. NGI report 581200-32, 1997).

Results: speed measurements and impact forces

The body of data and information in regard to impact pressures and speeds collected at Ryggfonn constitutes a continuous record of vital information over more than 15 years. The volumes of the 27 avalanches recorded through 1996 varied by three orders of magnitude (5000 to 500,000 m^3) with speed estimates ranging up to 60 m/s and impact pressures on the load cells as high as 540 kPa. These data records over many years of measuring give confidence to engineers trying to estimate design impact forces and speeds on avalanche paths. The vertical drop of Ryggfonn is about 900 m. McClung and Schaerer (1993) estimated that **maximum** speed scales as 1.8 $(H)^{0.5}$ where H is total vertical drop and flow density for dry avalanches is about 150 kg/m^3. For Ryggfonn this simple scaling gives 54 m/s for maximum speed and if impact pressures are calculated as the square of the speed and flow density, maximum speed implies impact of 540 kPa if the flow density is 150 kg/m^3 to give very good agreement for these simple, rough estimates. The long term records at Ryggfonn strengthen these simple scaling equations and estimates and there is consistency between the Norwegian data and experience from other countries including Canada and Switzerland.

The results about tension in transmission lines (Norem, et. al., 1985) are unique. They provide extremely useful information about impact forces as a function of height (8,12,16 m above the ground) above the dense core of dry flowing avalanches to enable conclusions to be made about flow densities for impact high on structures in the portion of the flow suspended in turbulent eddies as well as direct information about expected tension in transmission lines as input for design. No other data set exists to get the important information conveyed by these field experiments.

Avalanche dynamics modelling

The only known method to predict speeds along the incline to estimate impact forces or for design of defences is to use avalanche dynamics models. Further, the most important aspect of dynamics modelling is that for dry flowing avalanches with a dense core of rapidly deforming material at the bottom which is the most important control on the overall motion resistance. This is clearly a problem of great complexity in the real world in which flowing snow interacts with terrain roughness features. Quantitative formulation of the problem began seriously in 1955 with the publication of Voellmy's work which was formulated on the basis of limited field observations and experience partly by analogy to a problem in fluid flow with a solid friction component added to account for the observation that the material "locks up" with only basal sliding at slow speeds near the end of motion. Subsequent research has shown that dry flowing snow can be thought of as a dense (meaning the volume fraction filled by solid particles), rapidly deforming granular material. The volume fraction filled by solids is estimated to be in the range of 30-50% which implies that momentum is transferred within the mass by collision of particles or rubbing of particles against each other and bottom friction must consist of the same mechanisms expect particles also interact with the surface over which they are sliding.

As the problem became redefined by intensive research on mechanics of dense, rapidly deforming materials, theoretical work was initiated at NGI by Harald Norem in cooperation with Professor Fritjof Irgens at the Technical University in Trondheim and Bonsak Schieldrop, a private consultant, to develop a model which is suitable for applications but which also fits the physical constraints on the problem which were being developed by engineering mechanics specialists working on granular flows in general. The result was first brought to international attention at a meeting in Davos, Switzerland in 1986 (Norem, Irgens and Schieldrop, 1987). The resulting non-linear continuum model was a bold step to institute realistic physics into avalanche dynamics modelling. The model necessarily contains more parameters than previous models because it requires more parameters but such complexity is necessary if solutions are to be calculated for realistic geometries of avalanche paths and if extension is to be made to complicated material behaviour. The material parameters in the stress-strain-rate constitutive relations include: snow density, cohesion, internal friction, two normal stress viscosity parameters, a shear viscosity (all viscosities dependent on the rate of shearing) as well as four exponents to describe empirical rate of shearing dependence of the parameters. The model can also accommodate slip as well as no slip bottom boundary conditions. The resulting constitutive model results in a general non-linear fluid which reduces to Newtonian and Bingham fluid representations with simplifications easily made with assumptions about parameters. The basic one-dimensional model was put forward by Norem, et.al. (1987) and it was refined for analysis in the runout zone and for run-up by Norem, et.al. (1989). Extension to problems for which avalanches strike sloping deflecting dams at an angle was considered by Irgens, et.al.(1998).

Overall, the model has great flexibility to handle complex slope geometry (in one dimension) and constitutive assumptions which may be as simple or complex as the assumptions made to run it. Further, the model produces a prediction of the geometry of the deposit once motion ceases: a feature which potentially makes it far more realistic than the older generation of centre-of-mass models (Voellmy, 1955; Perla, Cheng and McClung, 1980) or the leading edge model of McClung and Mears (1995). The flexibility in specifying friction and viscosity parameters will prove useful as research into the complexity of dense, rapidly deforming bodies of granular material continues.

Summary: Avalanche speeds, impact pressures and dynamics modelling

The body of work on avalanche dynamics and the field measurements associated with contains outstanding contributions which are essential for land-use planning, design of defences in runout zones and for specification of expected forces on structures exposed to snow avalanches. The long term commitment of NGI to this work has resulted in a pool of information of general applicability in consulting applications. The field measurements are difficult and expensive but the information is found nowhere else. The avalanche dynamics modelling represents an innovative, bold approach with enough flexibility to handle complex boundary conditions, constitutive assumptions and slope geometries and it is consistent with the known properties of dense, rapidly deforming materials.

SUMMARY

The geotechnical research on snow and avalanches at NGI over the last 25 years constitutes an outstanding body of information on the key issues that are faced in Norway. The approach has been one of long term commitment to these problems until results are obtained. The long term approach is particularly important at NGI where there is no full time researcher on the problems. The wise approach of persistence and determination on key problems has resulted in outstanding, innovative approaches to the key problems. The statement: "Research doesn't cost, it pays." needs no further proof.

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