Snow Mechanics: Machine-Snow Interaction

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Response performance of snow is conditioned by the system within which it is stressed, boundary conditions, and initial conditions - not only with respect to the stress situation but also with respect to material properties, formation, and thermodynamic history. The shear resistance of snow is examined since this is considered to be a basic strength property of the material which participates fully in the development of snow shear resistance to applied stresses - such as those encountered in machine-snow interaction.

The changes in the state and character of snow from an unstressed region can readily be observed in the study of snow performance under load. Types of shear failure in snow however, are difficult to characterize or evaluate - both from a qualitative point of view and also from a quantitative viewpoint. The reasons are found in the fact that snow is an extremely varied material whose properties and characteristics are very sensitive to climatic, physiographic, temperature, thermodynamic history, and pressure dependent situation. Thus for example, variations in differences in snow properties and characteristics are found between tree-line snow and prairie snows, coastal as opposed to Alpine, Arctic as opposed to sub-Arctic snows, etc.

It has been noted from previous experiences in many other related fields of study that the mechanical response characteristics of any assembled material are dependent on the intergranular interaction, e.g. Yong and Warkentin, (1975). In that regard, the response characteristics of snow are also seen to be dependent on the type of intergranular force. In this sense, at least four main types of snow, consisting of various intergranular interactions can be identified - insofar as gross mechanical response characteristics are concerned. These are:

1. Fresh snow (with original crystal shape).
2. Granular snow.
3. Semi-bonded snow (with water film).
4. Sintered snow.

These types of snow change from one state to another with time and temperature. Thus, for example, fresh snow becomes sintered snow with time, and granular snow becomes a semi-bonded snow with temperature and is transformed to sintered snow with time. Note that this transformation of snow type is often accompanied by changes in density and grain characteristics as a function of time, temperature and pressure.

Taking into account the influence of climatic and physiographic factors, and other conditions such as time and local pressures which will contribute to the metamorphic processes of snow, it becomes obvious that for a proper appreciation of snow properties it is necessary to recognize:

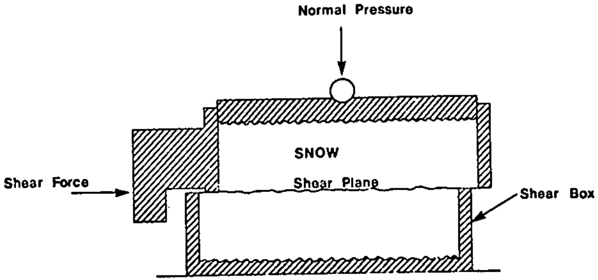
a. The problem of appropriate and varied characterization of snow.
b. The fact that the response performance of snow is conditioned by the type of snow, and also by the nature and manner of physical testing for assessment of snow properties.

In the case of machine-snow interaction - e.g. snow removal from machine ploughing or vehicle mobility on snow covered terrain, compressibility and shear resistance constitute the prime response mechanisms of the snow layer or snow pack. The performance of snow in confined compression has been reported previously by Yong and Fukue, (1977). The methods for determining the kinds of snow used, together with characteristics of the material in shear under confined status have been examined. In the study, the direct shear performance of snow is examined. These characteristics are seen to be fundamental to the development of machine-snow interaction phenomena.

Apparent Failure Modes in Direct Shear Performance

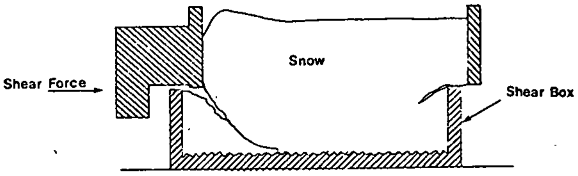
For granular snow, the failure mode exhibited in direct shear performance under sufficient normal stress is the "cutting shear" as shown in Figure 1. This is seen to correspond well with other types of granular materials. However, if snow is well sintered (bonded), the failure mode, without normal pressure or with relatively lower normal pressure, differs from the

Figure 1. General shear failure of snow in a direct shear test.



ordinary shear failure mode, as shown in Figure 2.

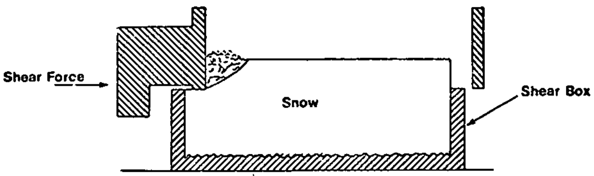
Figure 2. Typical tensile failure mode for snow without normal pressure or with relatively lower normal pressure in a direct shear test.



This failure mode may be identified as "tension failure" of well sintered snow in direct shear tests similar to the observations of Butkovich (1956) for double shear ring test on snow.

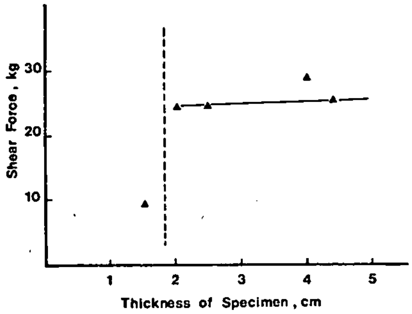
Note that in the evaluation of snow performance in direct shear, proper attention to boundary conditions and constraints is necessary. Figure 3 shows an irregular type of failure mode when the thickness of the shear layer of the snow specimen is very shallow.

Figure 3. Irregular failure mode of snow in a direct shear test when the thickness of specimen is insufficient. Note that the failure mechanism is not unlike that of snow cutting.



The occurrence of this irregular failure leads the very low shear resistance in comparison with the ordinary shear failure performance. This phenomenon is not unlike that developed in soil or metal cutting. If one wishes to examine the effect of thickness of snow specimen in direct shear performance, the thickness of the top shear layer can be expanded. This leads to the results shown in Figure 4. As can be observed, there is a limiting thickness of the shear layer, such that for a thickness of more than 2.0 cm, the shear force seems to remain almost constant as shown in the Figure. To maintain uniformity in testing, the shear tests conducted in this study required the thickness of snow specimens to be at least 3 cm thick in the upper layer above the shearing plane.

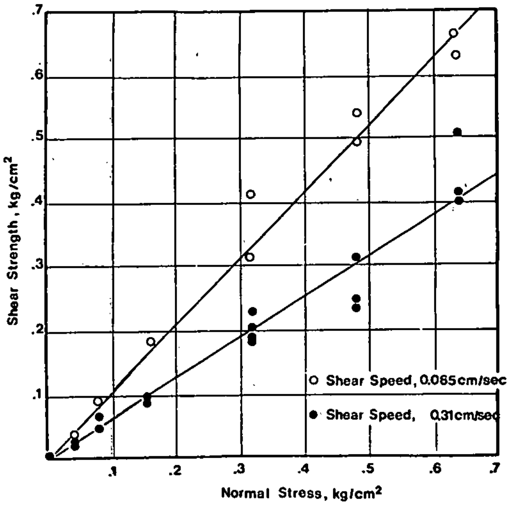
Figure 4. Shear force developed as a function of thickness of snow specimen in direct shear test.



Effects of Shear Velocity

Figure 5 shows the relationship between shear strength and normal pressure for the granular snow [used previously by Yong and Fukue, (1977)] at two ranges of shear velocities, e.g. 0.065 and 0.31 cm/sec.

Figure 5. Relationships between shear strength and normal pressure for granular snow in direct shear, tested at shear velocities of 0.065 and 0.31 cm/sec.



The open circles indicate the shear strength obtained at a shear velocity of 0.065 cm/sec, whilst the black circles indicate the shear strength for the same snow at a shear velocity of 0.31 cm/sec.

The results show that the relationship between shear strength τ and normal pressure σ_n is almost linear at both shear velocities of 0.065 and 0.31 cm/sec. This trend is not uncommon for granular materials.

The relationship between shear strength and normal pressure may be evaluated in a manner similar to that given by the Coulomb-Navier theory:

$$\tau = \sigma_n \tan \phi' \qquad (1)$$

where

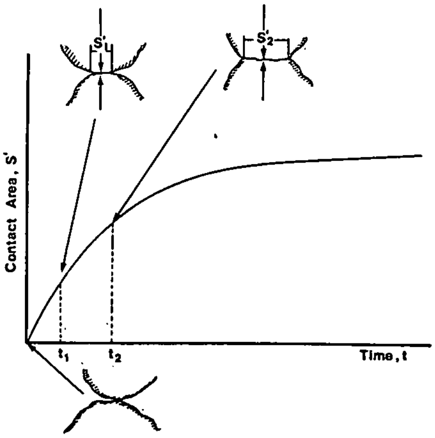
τ = shear strength
σ_n = normal pressure acting on the shear plane
ϕ' = apparent correlative angle

Note that the designation of ϕ' as the apparent correlative angle is deliberate. The temptation to identify ϕ' with the physical characteristic of block or particle friction should be discouraged. In the present context, ϕ' is taken as a mathematical correlative angle - and does in no way represent the friction angle of the material. Proponents of the Mohr-Coulomb theory will recognize the inherent dangers of application of the theory to a high volume change material. As shown in Figure 5, the apparent correlative angle ϕ' is strongly dependent upon the shear velocity. In this set of experimental results for example, we note that the apparent correlative angle ϕ' is 46° for a direct shear performance at a shear velocity of 0.065 cm/sec. This value reduces to 33° for tests at a shear velocity of 0.31 cm/sec. This suggests that the shear strength of snow decreases with the increasing shear velocity. This trend is not common with other materials.

Shearing Mechanism of Snow

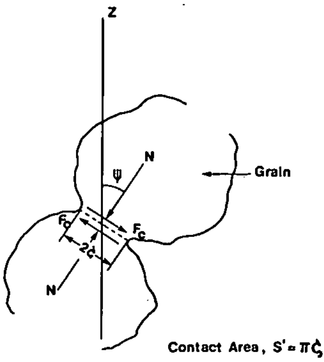
To obtain an appreciation of the implications of the apparent correlative angle ϕ' it is necessary to examine snow inter-granular activity under stress. It is known that the contact area between snow grains must increase with irrecoverable deformation in the absence of inter-granular slippage. To develop a simplistic picture, we consider firstly a point contact between two grains as shown in Figure 6. This Figure illustrates the relationship between grain contact area for a developed normal stress between grains as a function of the time taken to reach inter-granular slip [i.e. incipient shear failure]. If at time t equals zero, the corresponding load is zero, then the contact area for a granular snow condition can be considered to be very small or negligible.

Figure 6. Development of grain-to-grain contact area prior to shear failure as a function of speed of shear test. Note that times t_1 and t_2 represent time taken to reach incipient shear failure for two different shear loading velocities.



If loading occurs immediately after t = 0, one can envisage that under dynamic loading conditions, if the time taken to reach failure occurs at $t = t_1$, the contact area between grains increases to S_1'. Similarly, if the time taken to reach failure occurs at $t = t_2$, for a slower rate of loading, the contact area becomes S_2' as shown in the Figure. Under direct shear, the relationships formed by S_1, S_2 ..... S_n and t_1, t_2..... t_n with regard to different shear velocities are seen to be dependent on the time required to initiate or promote relative slippage of grains i.e. when slip between grains occurs the relationship between contact area development and time becomes affected. It is noted that at a lower shear velocity for example, a longer time period is required for the slippage or shear failure to occur. As shown in the Figure, if we assume that for slip to occur under conditions of a high shear velocity is for example t_1, and the time required to initiate slip at a particular lower shear velocity is t_2, the tangential forces required to initiate slippage between two adjacent snow grains in contact may be given by, [see Figure 7]:

Figure 7. General stress conditions at snow grain contact.



for $t = t_1$,

$$F_{c1} = A_c S_1' + N \tan \phi_i \qquad (2)$$

for $t = t_2$

$$F_{c2} = A_c S_2' + N \tan \phi_i \qquad (3)$$

where

F_{c1} and F_{c2} = the tangential forces to initiate slip for $t = t_1$ and $t = t_2$ respectively.
A_c = the adhesion per unit area on the contact, S_1' and S_2' are contact areas in relation to t_1 and t_2 respectively.
N = the normal pressure acting on the contact area
ϕ_i = the apparent correlative angle for the granular snow.

From the preceding statements, the condition can be written as :

$$F_{c1} < F_{c2} \qquad (4)$$

indicating thereby the situation where the higher the shear velocity, the smaller is the tangential force required to initiate slip between grains. This idea can be extended to account for similar phenomena in unconfined compression performances.

Writing equations 2 and 3 in a general form:

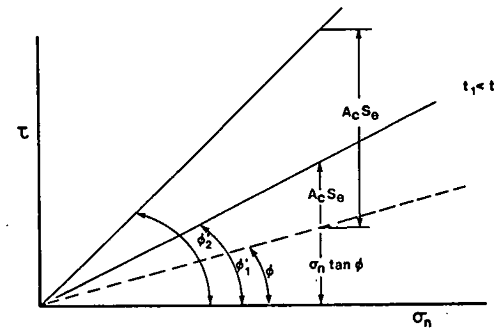
$$\tau = A_c S_e + \sigma_n \tan \phi \qquad (5)$$

where

τ = shear strength
A_c = adhesion per unit area
S_e = "effective contact area" of the specimen
σ_n = normal force acting on the shear plane
ϕ = apparent correlative angle for a granular snow condition [from the macroscopic point of view].

If one assumes that the apparent correlative angle ϕ is constant, then the experimental results obtained are explainable as shown in Figure 8. The Figure demonstrates that the shear strength of snow consists of a pseudo frictional characteristic dependent on the normal stress and an adhesive resistance component proportional to the effective contact area. The adhesive resistance component is seen to increase as the failure time increases because the longer time provides for a greater contact area. As noted earlier, a higher shear velocity provides for a shorter time for failure to occur in the snow. Therefore, one could deduce that the minimum shear strength of the snow can be obtained at a very high shear velocity since inter-granular slip can occur without sufficient development of grain contact area.

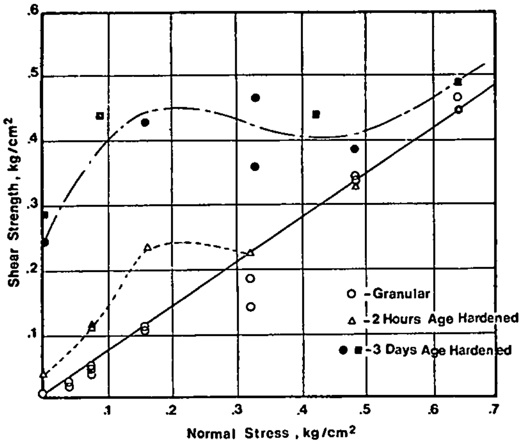
Figure 8. Illustration of shear strength showing adhesion component.



Effect of Initial Bonding of Snow in Direct Shear Test

To examine the influence of initial conditions [i.e. initial snow structure] on development of strength, direct shear tests on snow of various "ages" were tested. Figure 9 shows relationships between shear strength and normal stress obtained from differently age hardened snow. In these test series, various snows, i.e., granular snow obtained from laboratory preparation techniques reported previously by Yong and Fukue (1977), 2-hour age hardened granular snow and 3-day age hardened snow were examined. As noted, the basic snow used was a laboratory prepared granular snow whose grain size distribution was similar to that of a 5-day old fresh fallen snow - as reported by Yong and Fukue (1977). Granular snow is identified as an assemblage with discrete grains while age hardened snow is identified as sintered snow. The use of a laboratory prepared snow as a basic snow is necessary if one desires to control initial material properties. This provides one with a repeatable controlled uniform material for testing. As noted previously, the apparent relationship between shear strength τ and normal stress σ_n for granular snow is almost linear and the apparent correlative friction ϕ' is approximately 33° for a shear velocity of 0.31 cm/sec.

Figure 9. Relationships between shear strength and normal pressure for various age hardened snow in direct shear test.



The τ - σ_n curve of the 2-hour aged snow [indicated by the triangles in Figure 6] is not totally linear as shown. The results show that the non-linear part of curve for the aged snow appears under normal pressures of less than 0.3 kg/cm^2. Under greater normal pressures the relationship between τ and σ_n is seen to be almost linear as shown in the Figure. For the 3-day age hardened snow, the relationship shows that non-linearity in shear exists under normal pressures of less than 0.55 kg/cm^2. Since the age leads to bond development, the non-linearity between shear and normal stress is seen to be dependent upon establishment of bonds.

Concluding Remarks

The shear response behaviour of snow for the same test temperature condition is seen to be dependent on the following factors:

1. Snow type.
2. Normal pressure acting on the shear plane.
3. Shear velocity.

A simplistic structure model to explain the shear behaviour with respect to both snow type and normal pressure effects can be developed as shown in Figure 10. In Figure 10a the simple model shows the shearing characteristics of granular snow. The shear plane of the granular snow is initially indicated as a discontinuity - which means a no bonding condition between grains. From the engineering point of view, at relatively low temperatures, the water film effect between snow grains is not too pronounced.

Figures 10b - 10d illustrate the effects of normal pressure for sintered snow on the shearing characteristics of the snow. Figure 10b shows the behaviour

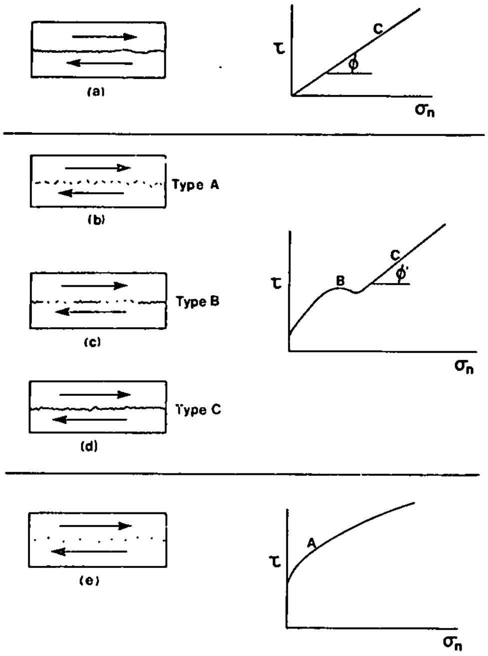


Figure 10. Typical shearing responses of snow in direct shear test in relation to snow type.

of the structural model without benefit of normal pressure or with relatively lower normal pressure - when no breakage of inter-granular bonds occurs. As noted earlier, tension failure occurs during shear application under relatively lower normal pressure. At this level of low normal pressures, the $\tau - \sigma_n$ curve shows a high gradient, indicated as Type A [Figure 10b]. If a higher normal pressure is applied during the shear process, micro-failure [i.e. the breaking of bonds] may occur. The phenomenon induced at this level of normal pressure is identified as Type B shown in the Figure. The apparent feature of Type B for the $\tau - \sigma_n$ curve is recognized as a very low or negative gradient performance of the curve as shown in the Figure. Note that a negative gradient of the $\tau - \sigma_n$ curve indicates a relaxation phenomenon brought about by the selective bond breakage sequence in the snow test specimen.

If a very high normal pressure is applied prior to and during shear, one might assume that almost complete breakage of the inter-granular bonds occurs. The final snow condition will reach a totally granular snow status. The density of the final granular snow condition is seen to be higher than the initial density because of the occurrence of microfractures due to inter-granular slip.

For a highly bonded snow or ice, the $\tau - \sigma_n$ curve obtained may be seen to be similar to those obtained from soft rock testing as shown in Figure 10e. This type of curve is similar to Type A and is similar to the $\tau - \sigma_n$ curve for high density snows tested by Butkovich (1956).

The shearing characteristics of snow in relation to snow types can be divided into three main types, i.e. sand-type granular snow, moderately bonded snow, and a rock-type strongly bonded snow. These distinctions must be taken into account in the evaluation of shear strength of snow - particularly with respect to machine-snow interaction considerations. A knowledge of the $\tau - \sigma_n$ variation with respect to both speed of shear application and normal pressures can lead to a proper selection of the kinds of tools and techniques for handling the snow material.

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