GEOTECHNICAL RESEARCH CENTRE

RECENT STUDIES IN SNOW MECHANICS AND TRAFFICABILITY

BY

RAYMOND N. YONG

&

VEHICLE MOBILITY LABORATORY STAFF

SOIL MECHANICS SERIES NO. 40

MAY 1978

McGill University
Montreal, Que Canada

Report to:
Defence Research
Establishment Ottawa

Department of Supply and Services
Contract No. 08SU CD. 3237007
Serial No. 2SU77-00067

ISSN 0541-6329

FOREWORD -

The problem of wheel and track snow interaction has been covered most recently and summarized insofar as McGill Vehicle Mobility Laboratory work for the 1977-1978 research year is concerned, in the two papers presented herein. These have been written for -

> *The Second International Symposium on Snow Removal and Ice Control Research, Hanover, New Hampshire, May 1978.*

> *The Canadian Society for Terrain-Vehicle Systems Symposium - ECONO-MOBILITY, Toronto, March 1978.*

Included also is a paper written by the *ISTVS Committee on Snow Mechanics Research Coordination* for -

> *The Sixth International Conference of the International Society for Terrain-Vehicle Systems, Vienna, August 1978.*

SNOW MECHANICS : MACHINE-SNOW INTERACTION

by

Raymond N. Yong* and Masa Fukue**

prepared for

SECOND INTERNATIONAL SYMPOSIUM

ON

SNOW REMOVAL AND ICE CONTROL RESEARCH

Hanover, New Hampshire

May 15-19, 1978

* McGill University, Canada.

** Tokai University, Japan.

SNOW MECHANICS : MACHINE-SNOW INTERACTION

Raymond N. Yong, McGill University
Masa Fukue, Tokai University

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 on the 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 characterisation of snow.

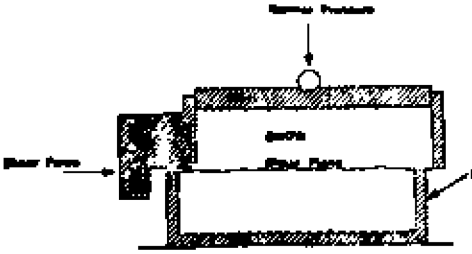
b. The fact that the response performance of snow is conditioned by the type of snow, and also by the nature and manner of physical testing for assessment of snow properties.

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.



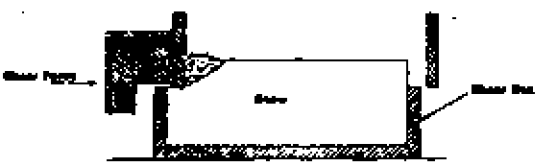
ordinary shear failure mode, as shown in Figure 2.

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.

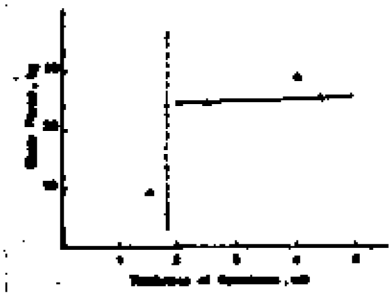
Note that in the evaluation of snow performance in direct shear, proper attention to boundary conditions and constraints is necessary. Figure 3 shows an irregular type of failure mode when the thickness of the shear layer of the snow specimen is very shallow.

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.

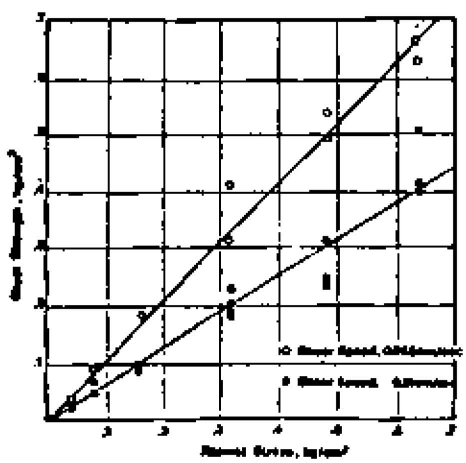
Figure 4. Shear force developed as a function of thickness of snow specimen in direct shear test.



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:

$$\tau = \sigma_n \tan \phi' \tag{1}$$

where

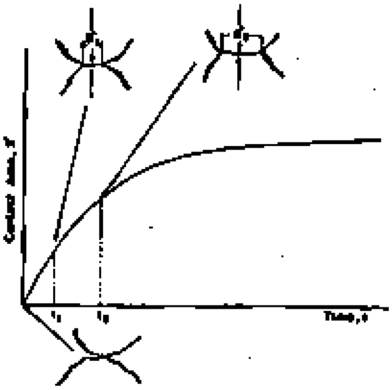
τ = shear strength
σ_n = normal pressure acting on the shear plane
ϕ' = apparent correlative angle

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

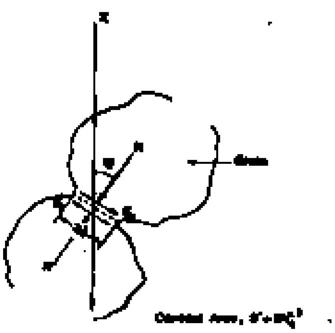
To obtain an appreciation of the implications of the apparent correlative angle ϕ' it is necessary to examine snow inter-granular activity under stress. It is known that the contact area between snow grains must increase with irrecoverable deformation in the absence of inter-granular slippage. To develop 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 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 become 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 $t = t_1$,

$$F_{c1} = A_c S_1' + N \tan \phi_i \tag{2}$$

for $t = t_2$

$$F_{c2} = A_c S_2' + N \tan \phi_i \tag{3}$$

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 acting on the contact
ϕ_i = the apparent correlative angle for the granular snow.

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

$$F_{c1} < F_{c2} \tag{4}$$

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 performance.

Writing equations 2 and 3 in a general form:

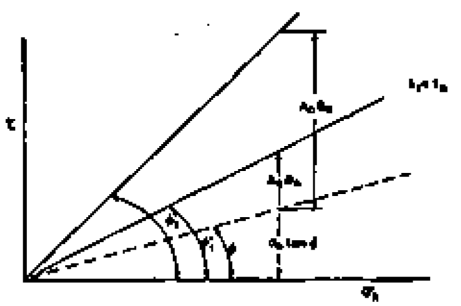
$$\tau = A_c S_e + \sigma_n \tan \phi \qquad (5)$$

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.

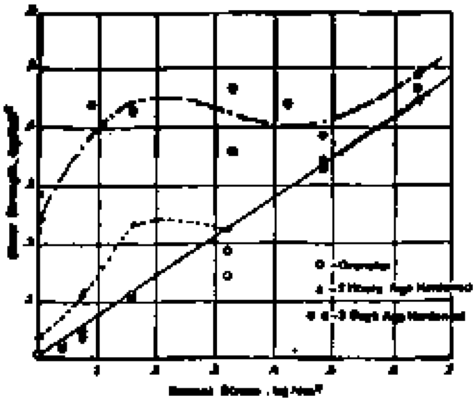


Effect of Initial Bonding of Snow in Direct Shear Test

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 3-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.

The $\tau - \sigma_n$ 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/cm². 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 0.35 kg/cm². Since the age leads to bond development, the non-linearity between shear and normal stress is seen to be dependent upon establishment of bonds.

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



Concluding Remarks

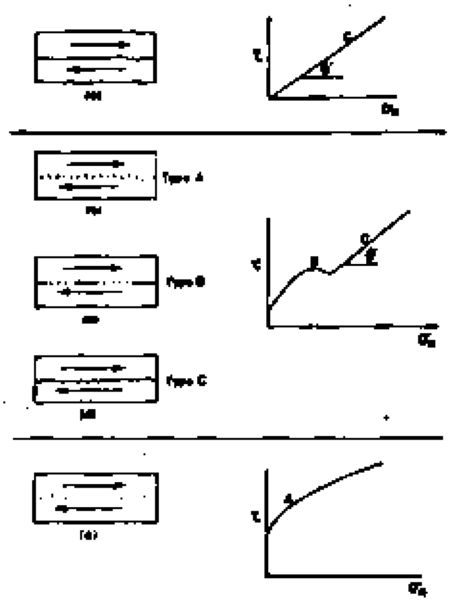
The shear response behaviour of snow for the same test temperature condition is seen to be dependent on the following factors:

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 pressure, 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 state. 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.

Acknowledgements

This study was conducted under contract arrangement with the Department of Supply and Services – with project administration from the Mobility Section of Defence Research Establishment, Ottawa (DREO). The assistance and input given by the Project Officer, Mr. I. J. Lindsay, Earth Sciences Division, are acknowledged.

References

1. R. N. Yong and B. P. Warkentin, Soil Properties and Behaviour. Elsevier Publishing Company, Amsterdam. 1975, 449 p.
2. R. N. Yong and H. Fukue. Performance of Snow in Confined Compression. Journal of Terramechanics, Vol.14:2, 1977, pp.59-82.
3. T. R. Butkovich. Strength Studies of High-Density Snow. USA SIPRE Research Report 18, 1956.

SNOW TRAFFICABILITY - THE KNOWLEDGE GAP

by

Raymond N. Yong and William L. Harrison

prepared for

Canadian Society for Terrain-Vehicle Systems
SYMPOSIUM

ECONO-MOBILITY

Toronto

March 30 - 31 1978

SNOW TRAFFICABILITY - THE KNOWLEDGE GAP

by

Raymond N. Yong[1] and William L. Harrison[2]

ABSTRACT

The wide differences in factors and parameters distinguishing snow trafficability from general appreication of *ordinary* soil trafficability are seen to demand proper recognition and attention. The problem of categorizing snow trafficability however is not easily solved since a simple one-to-one direct technology transfer from soil to snow mobility and trafficability cannot be implemented because of the very distinct different response performance of snow and the lack of available accepted or recognized schemes of identification and classification of snow.

INTRODUCTION

As a result of innumerable experiences and recent studies on various aspects of vehicle mobility on snow covered terrain, e.g. [1, 2][*]

---

1 William Scott Professor of Civil Engineering and Applied Mechanics; Director, Geotechnical Research Centre, McGill University, Montreal, Canada.

2 Research Civil Engineer, Applied Research Branch, U.S.Army CRREL, Hanover, New Hampshire, U.S.A.

* Numbers in parentheses refer to references in the bibliography.

it has become increasingly clear that there is a need to clarify the problems surrounding the mechanics of vehicle-snow interaction. In spite of the ready temptation to consider vehicle-snow interaction in terms of vehicle-soil interaction relying thereby on a simple transfer on a one-to-one basis of the methods of analysis, evaluation and assessment directly from soil trafficability considerations, it is necessary to bear in mind that the total response performance of snow can be diametrically opposite to that of soft soil. As noted by Yong and Harrison [2], under a large variety of snow conditions, the first pass of a vehicle in snow is generally the most demanding pass - i.e. insofar as snow trafficability is concerned, one would observe that the first pass is the worst pass. This contrasts vividly with the assessment of soil trafficability where by and large the first pass of the vehicle is the easiest pass, and succeeding passes on the soil terrain would require greater effort in order to produce the same traction. The many considerations leading to this particular set of statements have not been fully addressed.

In recognition of the severe complexities involved in defining the problem of snow trafficability, the ISTVS has recently formed an international committee to study this problem. Some of the aspects leading to the above statements have been considered in the first working paper developed by the Committee [3] whilst some of the considerations augmenting those given in [3] have been discussed by Yong and Harrison [2]. The intent of this study is to focus attention on the specific problem of snow trafficability, covering some of the points mentioned in [2] and [3] and some other aspects not previously noted.

Assessment of Vehicle Mobility and Terrain Trafficability

There are several methods used for assessment of vehicle mobility and terrain trafficability, e.g. [4, 5, 6]. By and large, these refer primarily to inorganic or some organic terrain material insofar as mobility and trafficability predictions are concerned. The assessment of some of the requirements from the available practices or techniques has been performed and summarized recently [7, 8]. The essence of the principles involved and current practices require:

(a) A knowledge or an assumption of the kind of vehicle-terrain interaction characteristics developed in the production of mobility - i.e. analyses or assumptions leading to the production or determination of forces resisting vehicle motion such as ploughing, drag, bull-dozing, slip, and other kinds of similar dissipative mechanisms.

(b) Some methods of determination or characterization of the ground support material whereby certain material *properties* are extracted for use in the development of analyses or calculations leading to support capability for the vehicle and associated losses.

(c) Empirical and correlative studies whereby vehicles are related to certain identifiable characteristics or properties of the terrain material - requiring

In essence field and laboratory testing procedures where actual experience of vehicle performance can be directly related to the terrain material, leading thereby to practical assessments and predictions of mobility and trafficability.

We note from the above that at least two specific points stand out very clearly. These are:

(1) A knowledge of the vehicle-terrain interaction characteristics.

(2) A proper means for identifying and classifying the material insofar as response performance is concerned.

Note that the wealth of testing experience for vehicles on soil terrain material is very large - in contrast to actual documented and rational studies of vehicles on snow covered terrain. In addition, it is pertinent to observe that the treatment of terrain soil material both as an active or passive material insofar as classification, identification, characterization, are concerned, can be found in many earth sciences disciplines. There are for example, several methods of classification and identification available depending upon one's particular discipline, i.e. soil science, geology, geography, geotechnical engineering, and agriculture. Arising from all these, it is possible to utilize the collective experiences from these disciplines for application to vehicle-soil terrain material interaction and to permit the development of a reasonable base for examination of the vehicle-soil terrain interaction phenomenon for assessment and prediction of vehicle mobility and terrain trafficability.

The problem of vehicle mobility on snow-covered terrain however is not as easily obtained or determined since:

(1) The methods and indeed the philosophies insofar as classification and identification of snow are not easily resolved.

(2) The interaction between vehicle and snow cover is indeed sensitive to the variable properties of snow.

The problem concerned with the proper identification and classification of snow for vehicle mobility purposes has been initially examined by the ISTVS Snow Committee [3]. Some of the observations made include:

(1) To predict or evaluate vehicle mobility in or through snow, there must be a quantitative definition of snow trafficability.

(2) Trafficability is dependent on, or a function of, particular vehicle types, sizes, running gears, loads, etc.

(3) A snow classification scheme designed for application to snow trafficability should be readily related to [or readily imply] the thermodynamic history of the material. This should include snow depth, wind velocity, prevailing winds, topography, layering, direction of metamorphism, etc.

(4) Snow trafficability also depends on terrain/topographical factors such as terrain geometry, non-uniformity of snow deposit and crustal formation, hardness of underlying terrain.

(5) Any trafficability prediction needs to be based on the snow condition at the time the vehicle is to attempt travel over or through the snow.

(6) Note that the present yield/failure criteria available and used, e.g. Mohr-Coulomb, pay no attention to strain at failure or yield. In addition, they are applicable only to no-volume change materials.

It is significant to note and to bear in mind that except for the high Arctic regions and the very high altitudes, snow cover and snow as a material do not exist as permanent entities. By and large, the life span of the material is less than six to eight months, with a three or four month period being the typical period for consideration. Because of its sensitivity to temperature and other climatic factors, it is clear that the material properties will vary not only with respect to its life span or cycle, but also with respect to local fluctuations within its life span - e.g. local climatic and environmental factors.

Snow Properties and Characterization

From the several recent studies on snow properties and characteristics [9, 10, 11, 12] the following points emerge:

(1) The high volume change characteristics of snow under compression and shear must be suitably accounted for in any analytical formulation.

(2) The effects of rates of loading on the material are sufficiently significant that these must also be factored into the analysis for strength and response characteristics.

(3) The distinction between fresh and aged snow insofar as properties and response performance is concerned, is large.

(4) In granular snow, the need to be able to distinguish between characteristic grain size, distribution and packing is evident.

(5) Snow property variation can be seen to be dependent upon time of day of test, location, temperature, speed exposure, etc.

The simple procedure of a transfer of technique or analysis from previously tried procedures as applied to the mobility on soft soil terrain problems, to considerations or analyses of mobility in snow will undoubtedly face complications and will lead to severe misinterpretations and obvious errors. The sensitivity of snow material response to all the various factors associated with microclimate, rate effects, thermodynamic history, and especially the boundary constraints imposed through methods of testing, render the requirements for a proper, knowledgeable, and sensible characterization of snow as being most significant. Thus for instance the accepted application of the Mohr-Coulomb theory of failure for inorganic soils whereby a friction angle ϕ and a cohesion C are obtained, needs to be carefully examined insofar as application to the problem of snow characterization. Since the constitutive performance of snow constitutes a major component in vehicle-snow interaction, it becomes particularly useful to learn the limits of applicability of constitutive or failure theories.

Informed proponents of the Mohr-Coulomb theory will observe that the demands of the theory require that the forces expended in shearing the material to failure are utilized solely at the plane of failure, or totally in shear failure, and that no volume change or or other losses of energy are accounted for. Note that this is a deficiency not of the analytical theory necessarily but of the available methods of field testing and measurement. In laboratory studies, the test and material situation can be controlled and sensible measurements made to provide for a rational development and application of constitutive theories. One needs also to bear in mind that the friction and cohesion parameters obtained from application of the Mohr-Coulomb theory are solely and absolutely a direct consequence of the mathematical theory of failure and not necessarily a representation of the physics of behaviour.

In view of the above, it is necessary to ask how these problems relate to the determination of failure in snow material. The application of Mohr-Coulomb's theory to the description of snow failure or to the description of snow properties, cannot be realistically accepted since the high volume change characteristics of the material under shear are not properly accounted for in the forces developed or measured. Where such values have been reported in the literature, it is understood that these do not have any measure of resemblance to the friction and cohesion parameters correspondingly used in the description of inorganic soils. The danger obviously lies in the application of such parameters to the standard theory developed in vehicle-inorganic soil interaction. It is necessary to bear in mind that the mechanisms and models developed in vehicle-inorganic soil interaction do not necessarily bear any relationship to the mechanisms developed in vehicle-snow interaction. In particular therefore if one then appreciates the problem of snow behaviour and the fictitious properties obtained thereby through misapplication of a theory, the problems are compounded and the answers derived cannot be easily deduced insofar as viabilities, acceptabilities, and realities are concerned.

There are many more such considerations with respect to snow property behaviour or variation. Some of these have been reported recently [10, 11, 12] and do indeed point up to the very pressing need for a knowledgeable understanding of snow behaviour and performance.

The Dilemma of Snow Trafficability

Following along the present general technique of using transfer of information on a one-to-one basis without specific appreciation of the wide variation and distinct contrasting characteristics between inorganic soil and snow, the problem of defining snow trafficability is particularly significant. In the ordinary definition of soil trafficability, the implicit understanding developed is that the material [inorganic soil terrain material] is classified or defined in terms of its ability to sustain vehicular loading in terms of a minimum number of vehicle passes. By and large, a figure of 50 passes is generally used to arrive at a means of identifying the trafficability of the soil material. Thus one would expect that if the material can sustain at least 50 passes of vehicular loading, it bears a certain trafficability characteristic. It follows that if it cannot sustain 50 passes, the classification for vehicular loading with respect to soil trafficability can also be defined. In most soil situations, as one continues to add more and more vehicular load passes to the soil, deterioration of the soil surface occurs to the point that more work is needed in order to provide for vehicular mobility. This results in a lessening of drawbar pull or a required increase in input to produce the same output. The exception to this might lie in some situations of sand packing where densification occurs under repeated passes.

In the case of snow, however, upon initial loading of the snow through one vehicle pass, if total immobilisation does not occur, the vehicle serves to compress the snow. The succeeding passes would now be made on a more compact snow thereby ensuring a better ability for succeeding vehicles to move over the snow terrain. Thus in essence the first pass of the vehicle on snow is generally more difficult than the succeeding passes over the snow covered terrain (snowpack). This identifies an exact polar position with soil trafficability considerations in that with succeeding passes on snowpack a greater densification of the snowpack occurs. The only exception to this might be found in a situation of crustal granular snow where succeeding passes might serve to break the crust and render the granular snow similar to that of the sand surface. However, with further and further tractive loading, especially from tracks, it is possible to induce a measure of compaction in the granular material to allow for at least no further deteriorating condition in the ground service and thus permit the material to remain trafficable.

The dilemma that now arises is one which requires the user to predict the properties of the material and to relate these properties to the capability for support of vehicles both in the first pass mode and in subsequent passes. It is necessary to produce a means to identify the material, not only in the present form but in particular with respect to its future role. To do that one needs to be able to determine the variations in the properties of the material with time and climatic changes as noted in [3]. In addition it is necessary to determine how these properties will relate or participate in the vehicle-snow interaction problem. Present techniques which depend solely on transfer of information, procedures, and practices from the vehicle-soil terrain interaction problem cannot be readily applied because they do not account for the diametrically contrasting behaviour for snow [as contrasted to soil]. In addition, the analytical techniques formulated for consideration and evaluation in vehicle-soil interaction cannot apply to the vehicle-snow interaction problem because the mechanisms of interaction are not similar. These are not immedediately evident and are therefore generally misused or misrepresented.

The tools to properly describe the material (snowpack) reacting with a vehicle, and the relationships established in interactions between snow and vehicle are not only absent, but not clearly understood or visualized. Much remains to be done to remedy the situation. Present technology or methods used in vehicle-snow studies suffer from inadequacies of understanding which need to be rectified. The discussions and recommendations forthcoming from the ISTVS Snow Committee [3] need to be seriously considered.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance received from their colleagues in their respective institutions [Defence Research Establishment, Ottawa (DREO) and U. S. Army Cold Regions Research and Engineering Laboratory (CRREL)], and for their support of the continuing overall study.

BIBLIOGRAPHY

[1] W. L. HARRISON, *Vehicle performance over snow; mathematical model validation*. U.S.A.CRREL, TR 268 (1975).

[2] R. N. YONG and W. L. HARRISON, *Evaluation of snow properties for analyses of vehicle performance in snow : Part I - Problem development and requirements for analysis*. Submitted to J. Terramechanics (1978).

[3] ISTVS COMMITTEE ON SNOW MECHANICS RESEARCH COORDINATION, *Requirement for identification and characterization of snow for mobility pruposes*. Sixth Int. Conf. ISTVS, Vienna (1978).

[4] M. G. BEKKER, *Introduction to Terrain-Vehicle Systems*, University of Michigan Press, Ann Arbor, Michigan. (1969).

[5] A. R. REECE, *Principles of soil-vehicle mechanics*. Proc. Institution of Mechanical Engineers (Automobile Division), Vol. 180, Part 2, p. 45. (1965).

[6] K. J. MELZER, *Power requirements for wheels operating in fine-grained soils*. Paper No. 72-617, Winter Meeting, American Society of Agricultural Engineers, Chicago, Illinois. (1972).

[7] R. N. YONG, *Analytical predictive performance for physical performance of mobility*. J. Terramechanics 10:47-60 (1973).

[8] R. N. YONG, C. K. CHEN and R. SYLVESTRE-WILLIAMS, *A study of the mechanics of cone indentation and its relation to soil-wheel interaction*. J. Terramechanics, Vol.9:1, pp.19-36. (1972).

[9] M. MELLOR, *Properties of snow*. U.S.A. CRREL Rept. III-A1, Part III:Engineering, Sect. A. Snow Engineering. (1964).

[10] W. L. HARRISON, *Study of snow values related to vehicle performance*. Report No. 23, Land Locomotion Research Board, OTAC. (1957).

[11] R. N. YONG and M. FUKUE, *Performance of snow in confined compression.* J. Terramechanics, 14:2, pp.59-82. (1977).

[12] R. N. YONG and M. FUKUE, *Snow mechanics : Machine-snow interaction.* 2nd Int. Symp. on Snow Removal and Ice Control Research, U.S. Army CRREL, Hanover. (1978).

REQUIREMENT FOR IDENTIFICATION AND CHARACTERIZATION OF SNOW FOR MOBILITY PURPOSES

by

ISTVS COMMITTEE ON SNOW MECHANICS RESEARCH COORDINATION*

prepared for

SIXTH INTERNATIONAL CONFERENCE

I.S.T.V.S.

Vienna

August 1978

REQUIREMENT FOR IDENTIFICATION AND CHARACTERIZATION OF SNOW FOR MOBILITY PURPOSES

by

ISTVS COMMITTEE ON SNOW MECHANICS RESEARCH COORDINATION*

ABSTRACT

The difficulties encountered in the determination of snow properties and characteristics which are relevant to the problem of snow trafficability are magnified by the lack of adequate means to properly identify and classify snow. The various components of the problem include:

(1) Thermal, mechanical, and time factors which influence the density and structure of snow, and its response characteristics.

(2) Changes in snow properties and response characteristics due to age and temperature histories.

(3) Methods of snow testing - recognizing that the response of snow is conditioned by the test instrument and technique.

(4) Procedures and criteria for identifying and classifying snow throughout the period of interest and for forecasting [prediction] purposes.

In this paper, the ISTVS Committee on Snow Mechanics Research Coordination discusses some of the above components of the problem to

---

* Committee Members: R.L.Brown, W.L.Harrison, G.J.Irwin, T.Muro, J.R.Radforth, G.Regli, J.Scholander, and R.N.Yong [Chairman].

illustrate and dramatize the need for establishment of (a) necessary standards and procedures to identify, classify, and test snow, and (b) proper relevant analyses of the test data for mobility analysis and prediction purposes.

INTRODUCTION

The three prime requirements in evaluation and analysis of off-road mobility are:

1. a knowledge of the properties of the vehicle, and in particular the running gear characteristics and morphology,
2. the properties and characteristics of the terrain being traversed, and
3. the vehicle-terrain interaction characteristics.

Many studies have been performed with respect to the classification and identification of terrain and ground subsoil [inorganic] characteristics and properties. By and large, the identification and classification of these terrain materials have followed empirical, semi-empirical and partly rigorous sets of rules. Assessment of the associated properties has been through various kinds of tests ranging from arbitrary to rational. The results from all of these have served as input to empirical or analytical models which permit the systems analysts to arrive at predictions of off-road mobility and capability - either in general terms or with respect to particular vehicles and their operational requirements.

In situation where snow cover becomes a significant factor insofar as terrain cover is concerned, considerations of off-road mobility must obviously include proper evaluation and accounting for snow participation in the production of vehicle mobility. If the same information such as those used in soils, e.g. soil-terrain identification, classification and property assessment are sought for snow, it becomes immediately apparent that much of the information available is either inappropriate or invalid insofar as snow trafficability or mobility on snow is concerned. This predicament is not surprising since it has been recently that attention to snow has been considered in mobility purposes. Past attention to snow as a material for study has generally been confined to scientific and engineering disciplines other than off-road mobility.

In view of the above, and with due recognition of the fact that continued concern for vehicle mobility on or through snow cannot be fully realized without proper attention to those aspects of snow which impact directly on vehicle mobility, the ISTVS Committee on Snow Mechanics Research Coordination was recently established to address the problem at hand. In this first report, whilst the Committee recognizes the vital appreciation for:

1. the need for a commonly accepted scheme for classification of snow specifically for snow trafficability purposes - i.e. the requirement for establishment of a list of snow parameters which affect vehicle mobility on and through snow - including vehicle-snow interaction considerations,

2. specification of procedures and methods of snow testing both in the field and in the laboratory for determination of the pertinent snow parameters for input to evaluation, prediction and design purposes for vehicle performance,

3. the need for research [and reporting] on snow mechanics as it relates to vehicles operating on or through snow,

it proposes to develop the overall vehicle-snow mobility problem by initially focussing on the *Requirement for Identification and Characterization of Snow for Mobility Purposes*. In subsequent reports, the Committee expects to present the other *Concerns* in order to provide further impetus to the necessary research into the problem, and also to coordinate the available information for use in research, application and development.

IDENTIFICATION AND CHARACTERIZATION OF SNOW

There are many aspects to the identification and characterization of snow. The primary one requires that these be directed specifically to the problem of vehicle operation in snow-covered terrain. For simplicity in presentation and discussion, identification of snow will be considered in terms of classification whilst characterization of snow will refer to the description of snow in relation to specific properties. With this in mind, the first concern expressed herein is with regard to classification of snow.

Previous classification systems of snow are, for the most part, inappropriate for use in snow trafficability considerations. For instance, whilst La Chapelle-Sommerfeld system [1,2]* is widely recognized and used on the American continent, it is not directly applicable since it is mainly a scientific tool which classifies snow according to its crystal geometry. As such, the system uses totally optical methods to observe snow structure for the purpose of describing the micro-structural properties of the material, and hence does not lend itself easily for the calculation of mechanical properties of the snow.** The complete meteorological and thermodynamic history of the material is reflected in the particular classification that a snow sample is placed in. For example, the snow that has gone through a temperature gradient process and then through melt metamorphism is placed in a classification of its own, based on the grain structure that this thermal process results in.

Temperature gradient or constructive metamorphism tends to decrease density and bearing strength while grain sizes increase. On the other hand, destructive or equitemperature metamorphism promotes densification and strengthening of the snowpack. Such conditions may occur anywhere in the snowpack and may modify the total behaviour of the pack under loading. Whilst a magnifying glass and a thermometer are all that is needed for initial field assessment or metamorphic description, accuracy or precision can only be obtained with experience coupled with laboratory confirmations. Unfortunately, at the present time, much work is required to render this classification system sufficiently

---

* Numbers in brackets refer to references in bibliography.

**Research in this problem area should remedy the situation.

accurate or amenable to relate snow loading schemes such as those imposed by vehicular activity to response mechanisms and relevant snow mechanical properties.

Requirements for Identification/Classification

It is apparent that classification of a material can take several forms and directions. This is particularly true in the case of snow since the interest in regard to the material is not with respect to a physical microstructural description of the material, but with respect to the performance of the material when it is subject to several kinds of load and deformation schemes.

If one rejects the microstructural approach for classification - similar to the one used for example in the La Chapelle-Sommerfeld system, because of the immediate inapplicability of the system to respond to the demands of the problem at hand, the alternate scheme for classification would obviously need to rely on descriptions arising from macroscopic observations. It may be, however, that a macro observation may not be sufficiently elementary to allow for the development of a dependable relation with mode of loading. Regardless of the method chosen, the objective of a proper classification scheme for snow trafficability should:

Reflect the thermodynamic history of the material, i.e. it should provide some quantitative indication of the temperature history and temperature gradient history of the material. In doing so, the degree of metamorphism that the material has been subjected to, grain size distribution, shape and intergranular bonding can perhaps be statistically deduced.

Note however that *trafficability* per se is relative to particular types of vehicles and running gear configurations.* Thus, in developing the kind and structure of a classification scheme for snow, it is necessary to differentiate between independent and dependent parameters.

It should be remarked at this stage that whilst it is desirable to provide as complete a description of the material [snow] as possible to meet the objective listed previously, the limitations and constraints imposed would inevitably require that the total identification and characterization procedure [for snow] be developed along the lines of simple field techniques and proper laboratory test procedures. The use of simple field techniques allows one to provide the basic information necessary for a classification scheme. The added information gained in laboratory tests falls into two categories: (a) information of a descriptive nature which will extend and confirm the classification of the material obtained through the simple field techniques, and (b) complex test information relating to performance characteristics and response properties. In the latter instance, this information becomes particularly useful in providing a description of the characteristics of the material -

---

* As noted by Yong and Harrison [3] snow trafficability increases with more vehicle passes - as contrasted to soil trafficability. Snowpack provides a better load carrying capability with increasing passes since a greater densification is achieved. Thus, as indicated by Yong and Harrison, in snow trafficability considerations, *the first pass is the worst pass*. If one survives the first pass, the chances of a successful second pass are indeed greater!

beyond that provided by the classification scheme. In other words, the simple classification scheme relies on simple field techniques and visual observations easily obtained in the field, whilst the more complex detailing of the material which must rely on further study using more sophisticated instruments and test techniques is in essence a *characterization* of the performance aspects of the material. As such, it is best to define this aspect as 'characterization', i.e. complex classification. To avoid confusion, the term 'characterization' will be used.

Simple Classification Requirements

The information required and easily obtained to satisfy the requirements for simple classification includes:

temperature profile and history

density profile

time of sampling

grain size distribution at time of sampling

grain geometry and initial assessment of bonding

compressibility under a single static load and density change

resistance to penetration [from a cone or equivalent]

shear resistance [using a field vane device or equivalent]

Note that resistance to penetration and shear resistance may be obtained following compressibility assessment. In this manner, a more consistent and realistic picture of the simple mechanical response of the material can be obtained. The rationale underlying this method of compressibility pre-condition of the material can be found in the fact that the material will develop critical or threshold densities [3] which are indeed characteristic of the material at that particular time and situation, i.e. characteristic of the grain size distribution, temperature, and grain geometry. Hence the simple classification scheme will require that compressibility measurements be made, following which shear and penetration resistances will be determined.

Requirements for Characterization

A good comprehensive identification scheme should include details of the material which inform the user about its response characteristics. This generally takes the form of constitutive relationships and yield/failure criteria. Other relevant properties used to describe the material performance characteristics, such as volume change under load, and strain-rate susceptibility can be useful information. Such properties as "Young's" modulus [stress-strain modulus] and associated parameters are in actuality direct interpretations of the constitutive relationships. Note that "Young's" modulus per se does not really apply since this refers to linearity and recoverability in stress-strain relationships.

Before discussing further the important characteristics that would be needed to complete the total identification/classification of the material, it is perhaps necessary to first consider the details of snow response to vehicle tractive loading. Examination of the basic mechanisms involved in a vehicle-snow interaction phenomenon will indicate that the expenditure of energy from the driving force [vehicle drive train] takes the form of slip and deformation production in the snow. The mechanisms of deformation and distortion on the snow can be broken down into compressional performance under normal and shearing stresses, and also shear distortional behaviour as a separate phenomenon. Since load application at the interface can be extremely high, resulting in high shear distortion at correspondingly high strain rates, the parameters of interest center around mechanical properties and their sensitivity to load-time boundary conditions. In view of the susceptibility of the material to temperature changes insofar as performance characteristics are concerned - especially under high shear rates, it can be argued that the viscous flow rate of the material would need to be determined [4,5,6]. Observations of local melt under high shear such as that condition found in the slip region would tend to support this proposition.

In the deformation zone, compressibility performance under various rates of load application and confinement effect need to be determined [7]. It is apparent that the various kinds of mechanisms developed by the snow in response to external stressing conditions should be categorized simply and effectively - perhaps into parameters that can be determined in the laboratory as standardized procedures and test techniques.

The mechanical properties that need to be determined to provide for a proper characterization of the material for snow trafficability considerations can be summarized as follows:

Constitutive and rheologic performance

Yield/failure criterion

Viscous flow parameters

Density changes under specified loading conditons

Shear strength

Water content, density, etc. at time of strength testing.

Test Measurements and Techniques

Because of the sensitivity of the material to test boundary conditions in addition to other local environmental factors, it is apparent that standardized procedures must be developed for both field and laboratory tests. Some of the more recent field tools used to provide information on snow response have been examined with respect to vehicle-snow interaction requirements [3]. At a later stage, the Committee will endeavour to document more detailed information regarding test procedures and methods. For the present, it is pertinent to observe that because of the varied kinds of tests used, and in view of the various types of analytical procedures used to derive predictions on mobility, there is little common agreement on what constitutes proper and pertinent tests for snow classification and characterization.

Coupled with the need for developing standardized procedures for testing in the field and laboratory, there also exists the need for production of a method of sample procurement that would maintain the integrity of the snow sample. This presumes that the associated factors of identification of the material in-place have been satisfactorily fulfilled.

CONCLUDING REMARKS

The object of this particular presentation is to provide a working basis for users in the vehicle-snow interaction problem to contribute their experience, knowledge and input to the Committee in order that a common basis for communication of the pertinent snow trafficability information can be made to the user, designer, system analyst, researcher, developer, etc. The following points bear detailing:*

1. To predict or evaluate vehicle mobility in or through snow, there must be a quantitative definition of snow trafficability. This is not presently available. Can this be defined?

2. Trafficability is dependent on, or a function of, particular vehicle types, sizes, running gears, loads, etc. Can we specify standardized vehicles, configurations, and conditions? Note that as noted by Yong and Harrison [3] in snow trafficability, since snow compressed and densified after a single vehicle pass, subsequent passes should find the snowpack more amenable for load support. Thus, in snow trafficability, as noted by Yong and Harrison [3], *the first pass is the worst pass.*

---

* Figures 1 and 2 illustrate the wide variability in 'strength' readings in two typical snow deposits in late winter. Note that the information obtained can be rendered meaningful if more supportive information is provided. The question remains as to "what kind"?

3. A snow classification scheme designed for application to snow trafficability should be readily related to [or readily imply] the thermodynamic history of the material. This should include snow depth, wind velocity, prevailing winds, topography, layering, direction of metamorphism, etc.

4. Snow trafficability also depends on terrain/topographical factors such as terrain geometry, non-uniformity of snow deposit and crustal formation, hardness of underlying terrain.

5. Any trafficability prediction needs to be based on the snow condition at the time the vehicle is to attempt travel over or through the snow. Therefore, although snow condition depends on the deposition and aging history of the snow, knowledge of that history should not be necessary to describe the snow for classification purposes, i.e. a knowledge of history serves as an aid to prediction but is not essential.

   A classification scheme provides the language of snow description. A field oriented classification system should serve to describe snowpack conditions. Means must be found to tie this to trafficability and mobility.

6. Snow classification research should focus on measurement of initial and ultimate compressive and shear strength of snow in various conditions to allow for a proper descript-

ion of the material compatible with trafficability requirements. This latter aspect requires considerable research and discussion to arrive at a mutually acceptable set of criteria - i.e. acceptable to all segments of the user, designer, developer population.

7. The central objective of research into the mechanical performance characteristics of snow, and the relevant properties of snow, should be to relate snow classes to vehicle performance in quantitative terms so that a knowledge of the snow condition would enable the reliable prediction of 'go' or 'no-go' for a given condition. A more useful capability would be to produce the situation which would permit prediction of the amount of drawbar pull that might be generated.

8. The load conditions that need to be investigated must include rate effects, repetition of loads, load boundary simulation identified with the various load traction devices employed on present snow vehicles.

9. Note that the present yield/failure criteria available and used, e.g. Mohr-Coulomb, pay no attention to strain at failure or yield. In addition, they are applicable only to no-volume change materials.

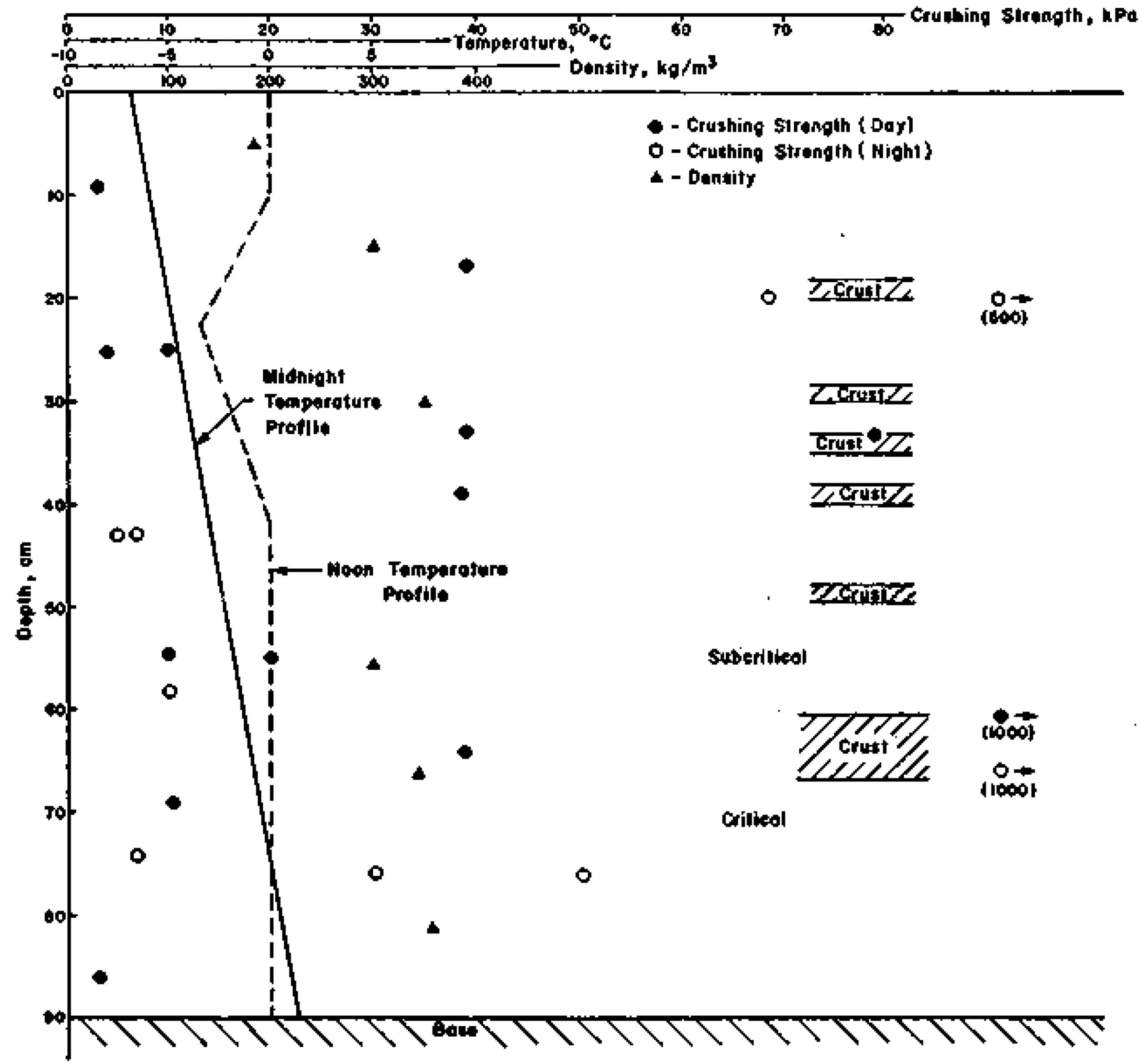


Fig. 1 Temperate Zone Snow (Southern Ontario in Late Winter)

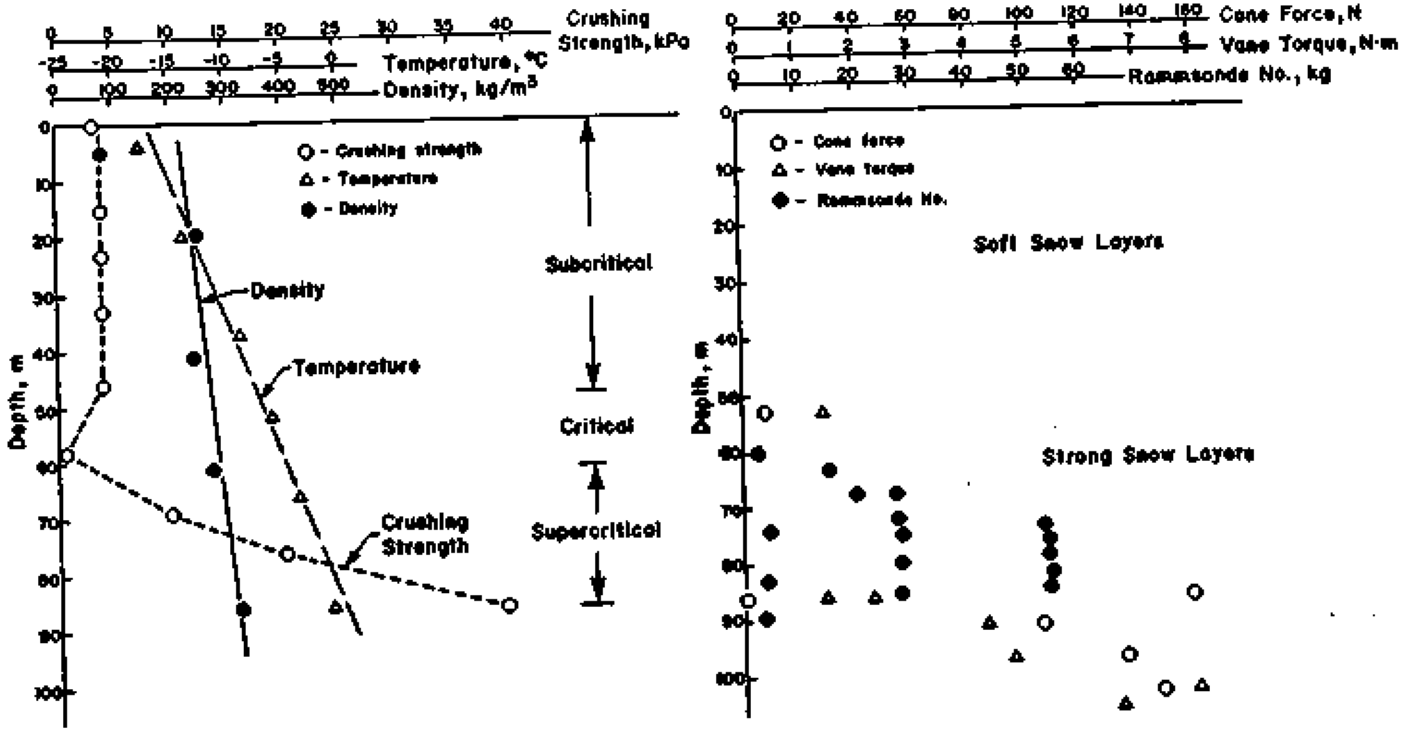


Fig. 2. Typical Woodland Snow in Late Winter. Air Temperature = -23°C

REFERENCES

1. R. A. Sommerfeld, *Classification Outline for Snow on the Ground.* USDA Forest Service Research Paper RM-48. (1969).

2. R. A. Sommerfeld and E. LaChapelle, *The Classification of Snow Metamorphism.* J. of Glaciology, Vol.9:55, pp.3-17. (1970).

3. R. N. Yong and W. L. Harrison, *On Vehicle Mobility in Snow Covered Terrain. Part I : Problem development and requirements for analysis.* Submitted to J. of Terramechanics (1978).

4. R. L. Brown, *A Volumetric Constitutive Law for Snow subjected to Large Strains and Strain Rates.* (Forthcoming as a CRREL Report.)

5. R. L. Brown, *The Application of a Dynamic Constitutive Law to Shock Waves in Snow.* (Forthcoming as a CRREL Report.)

6. R. L. Brown, *A Study of Vehicle Performance in Snow.* Submitted to J. of Terramechanics. (1978).

7. R. N. Yong and M. Fukue, *Performance of Snow in Confined Compression.* J. of Terramechanics, Vol. 14:2, pp.59-82. (1977).