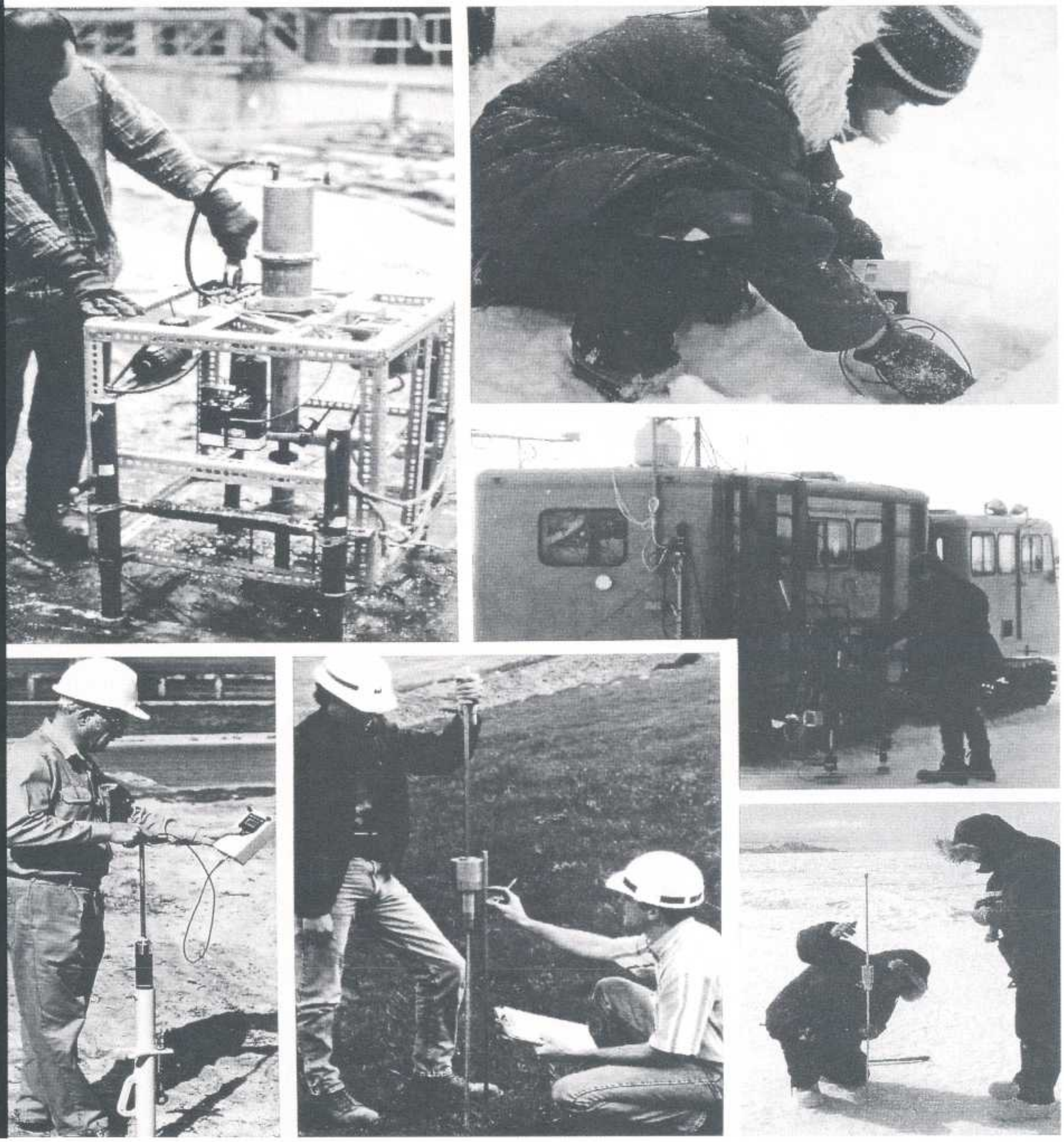
CRREL REPORT 93-6

CRREL

Terrain Characterization for Trafficability

Sally A. Shoop

June 1993



Abstract
Terrain material characterization is needed to predict off-road vehicle performance, trafficability, and deformation (compaction and rutting) resulting from vehicle passage. This type of information is used by agricultural engineers, foresters, military engineers, the auto and tire industry, and anyone else concerned with off-road, unpaved, or winter mobility. This report appraises the state-of-the-art of terrain (or substrate) characterization techniques for vehicle traction studies. It concentrates on field measurement of strength-related properties for soil, snow, muskeg, and vegetation, but also discusses how these compare with laboratory measurements and the importance of other terrain features (slopes, drainage, and obstacles).

Cover: Clockwise starting from upper left: Portable shear annulus (CRREL); liquid water content measurement in snow using a Denoth Dielectric Meter (Institut für Experimentalphysik, Universität Innsbruck, Austria); bevameter mounted on a Polecat (photo compliments of the Keewenaw Research Center, Houghton, Mich.); AARI penetrometer in Antarctica (compliments of the Arctic and Antarctic Research Institute, St. Petersburg, Russia); dynamic cone penetrometer (Waterways Experiment Station, Vicksburg, Miss.); and Clegg impact soil tester (compliments of Lafayette Instruments, Lafayette, Ind.).

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Standard Practice for Use of the International System of Units (SI)*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 93-6

US Army Corps
of Engineers
Cold Regions Research &
Engineering Laboratory

Terrain Characterization for Trafficability

Sally A. Shoop

June 1993

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Sally A. Shoop, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by DA Project 4A762784AT42, *Design, Construction, and Operations Technology for Cold Regions*; Task CS, Work Unit 007, *Off-Road Mobility in Thawing Soils*.

The report was originally written to be included in an American Society of Agricultural Engineers monograph on traction mechanics, *Advances in Soil Dynamics*, edited by Sverker Persson.

The author expresses her gratitude to Leonard Della-Moretta (Ret.), U.S. Forest Service, Technology and Development Center, San Dimas, California; Dr. Ronald Liston of USA CRREL; and Warren Grabau (Ret.), Newell Murphy, and Richard Gillespie of the U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, for their thorough technical reviews; Maria Bergstad for style and grammar edit; and William Bates for drafting the figures.

CONTENTS

ILLUSTRATIONS

Figure Page

TABLES

Table

Terrain Characterization for Trafficability

SALLY A. SHOOP

INTRODUCTION

This report appraises the state-of-the-art for characterizing terrain material (or substrate) for off-road vehicle traction or trafficability studies. It was originally written for inclusion in *Traction Mechanics* (Persson, in preparation), a monograph in the Advances in Soil Dynamics series of the American Society of Agricultural Engineers. Therefore, although I concentrate on soil strength characterization, which is of primary importance to agricultural engineers, I also include the unique aspects of other surfaces such as snow and organic terrain, of particular interest to military and forest engineers and others dealing with operation of off-road vehicles. The emphasis is on field measurements, with brief mention of their comparison to laboratory techniques.

Terrain includes the material that comprises the terrain (soil, snow, vegetation) as well as the geometry of the terrain surface (topography). The ability of the terrain to support and provide traction for vehicle operation is called *trafficability*. In trafficability studies, the emphasis is on the interaction between the vehicle and the surface material, whereas *mobility* considers the entire effects of the terrain, including obstacles and topography, on vehicle operation. This report focuses on the terrain material properties that influence trafficability and includes a brief discussion of other effects to be considered for off-road mobility, such as terrain features (slopes, obstacles, drainage) and climatic effects on the terrain environment (changes in moisture, freeze–thaw).

A means of characterizing the surface material is needed to predict off-road vehicle performance, trafficability, and soil deformation (compaction and rutting) that results from vehicle passage. Predictive models calculate the forces developed between the wheels or tracks and the terrain surface and generally assume the surface material is a well-behaved continuum (perhaps a bold assumption). A good review of various predictive models, along with their theoretical and experimental basis, is given in Plackett (1985). Each model may require different material properties as input, and although many different methods of material characterization exist, none is universally adequate. The same is true of the predictive models. It is of the utmost importance that the strength characterization technique satisfy the need for the information and be suitable for the terrain material in question.

SOIL

The fundamental parameters commonly used to describe soil for engineering or agricultural purposes are soil type, structure, grain size distribution, Atterberg limits, moisture content, and density. These and other physical properties of soils, as well as how they influence soil strength, are fully described in Chancellor (1993). The strength of soil depends on these basic physical properties. Measuring soil strength in the field rather than the laboratory has the advantage of testing the soil in its natural state. It is also generally less expensive and less time-consuming. Although carefully controlled laboratory tests may be more exact theoretically, they are impractical for a quick assessment of field terrain strength.

Penetration resistance

The field of traction mechanics has a keen interest in developing an easy and accurate field tool for terrain characterization for vehicle traction studies. One of the most popular tools, which the U.S. Army uses extensively, is the hand-held cone penetrometer (Fig. 1) described in ASAE standard S313.2 (ASAE 1985), SAE Standard J939 (SAE 1967), and U.S. Army Technical Manual 5-330 on Soils Trafficability (U.S. Army 1968). The hand-held cone penetrometer is a simple instrument designed to give a quick and easily obtained index of soil strength. The standard WES (Waterways Experiment Station) cone penetrometer consists of a proving ring, or some other force recording device, and a choice of two sizes of 30° cones. The large cone has a 323-mm^2 (0.5-in.^{2}) base area (15.9-mm-diameter shaft) and is used with soft soils and sands. For harder soils and soils with fines, a smaller cone, 130-mm^2 (0.2-in.^{2}) base area with a narrow shaft, is used.

The force required to press the cone through the soil layers is called the cone index (CI). Five to seven penetrations should be performed to get a good statistical average and an estimate of the variability of the terrain both laterally and with depth. The cone is pressed into the soil at a uniform rate of approximately 30 mm/s (72 in./min), although this rate may not be achievable in harder soils. The first reading is taken when the base of the cone is flush with the soil surface and then every 25 or 50 mm (1 or 2 in.) thereafter, depending on the application. The index is reported with depth, as an average over a range of depths or as a gradient.

For fine-grained soils, a remolding test may also be performed. The remolded sample is obtained by subjecting a 50.8-mm (2-in.) radius by 152.4-mm (6-in.) height soil sample contained in a tube to 100 blows (for fine-grained soils, or 25 blows for sands with fines) with a 1.14-kg (2.5-lb) remolding cylinder dropped from a height of 0.3 m (12 in.). The cone penetrometer is then used to measure the cone index of the remolded soil. The ratio of the remolded CI to the original CI is called a remolding index (RI). The product of the CI and the RI is called the rating cone index (RCI) and is a measure of the soil response to repetitive loads, such as multiple vehicle passes.

A vehicle cone index (VCI) is obtained using vehicle weight, dimensions, engine, and transmission factors in a series of equations and graphs detailed in U.S. Army TM 5-330 (U.S. Army 1968). The VCI is representative of the minimum RCI required for 50 passes of the vehicle. A comparison of the VCI and the soil RCI will result in a prediction of whether the vehicle is mobile or not in a particular soil.

Several adaptations have been made to the basic hand-held cone penetrometer, primarily in the form of continuous readouts, electronic data acquisition, and hydraulic rather than manual applied pressure (Olsen 1987; Rawitz and Margolin 1991). In these advances, the proving ring is replaced with a load cell, and the depth of penetration is measured with a proximity sensor. The output of the device is then automatically recorded on a data storage module or data logger. These developments allow full characterization of an inhomogeneous material in an efficient manner and at a low cost.

A similar device is the drop cone (Godwin et al. 1991), in which a 2-kg, 30° cone is dropped from a height of 1 m. This has the advantage of imparting a large force on the soil without the need to transport large weights or hydraulic equipment to the field (as would be needed to impart large forces with the standard "static" cone penetration). Tests at several field sites indicate linear rela-

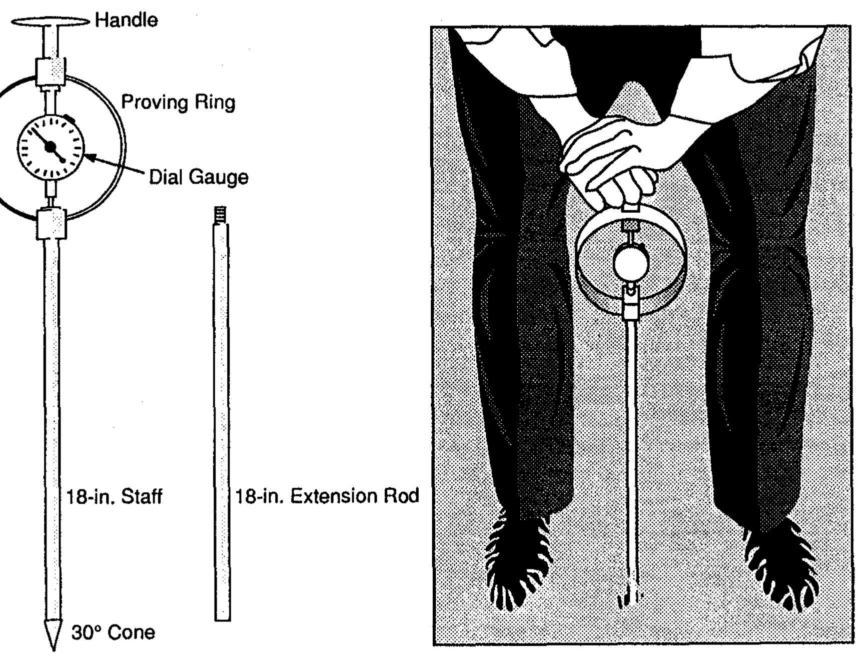


Figure 1. Hand-held cone penetrometer (after ASAE 1985, SAE 1967).

tionships between the drop cone penetration and soil moisture, vane shear strength indices, and mean wheel rut depth, enabling prediction of soil and crop damage from driving machinery in the field (Godwin et al. 1991). Another impact device, the Clegg Impact Soil Tester, is used to assess the condition of low-volume unsurfaced roads (Mathur and Coghlan 1987) and has also been effective at monitoring soil strength recovery after spring thaw for assessing trafficability (Alkire and Winters 1986). The variation of impact measurements within a site is less than for other hand-held tools because of the larger soil volume incorporated in the test. For this same reason, some researchers have found that the drop cone is not sensitive enough and prefer the static penetrometer.

The penetration resistance measured by cone penetrometers is determined by a combination of soil strength properties: shear, compression, tension, and soil/metal friction. To use mobility prediction techniques that rely on the more fundamental soil properties, Rohani and Baladi (1981) developed relationships between the cone index and the shear strength and stiffness of the soil. Unfortunately, these relationships work only for homogeneous, frictional soils. Using the theory they developed, a cone index can be calculated knowing the cohesion, friction angle, and stiffness of the soil, however, the inverse procedure is more difficult because of the number of unknowns. A solution to this inverse problem was proposed by Hettiaratchi and Liang (1987) for a drop indenter (cone) test. By carefully choosing the geometry of the indenter and the type of tests performed, solutions to a mathematical model of the soil indenter can be achieved based on cavity expansion theory. The solutions are presented in the form of nomograms relating indentation to soil strength.

A series of controlled experiments to determine the relationship between penetration and soil strength was performed by Mulqueen et al. (1977). Their conclusions are that the relative proportions of the different strengths (shear, compression, and tension) reflected in the cone readings vary with moisture content and the cone becomes insensitive to shear strength as the moisture content increases. In addition, while performing the experiments they noted that soil compacted ahead of the cone effectively changed the shape of the cone and that the cone shaft sometimes interfered with the readings.

Similarly, several researchers have studied the effects of soil physical properties on cone resistance (Collins 1971, Voorhees and Walker 1977, Wells and Tresuwan 1977, Ayers and Perumpral 1982, etc.). A good review of the factors affecting the penetration resistance—water content, bulk density, root density, soil structure, penetration rate, and soil type—is given in Perumpral (1987).

The cone penetrometer is very useful for determining go/no-go scenarios based on a large database of known vehicles. Problems may be encountered, however, in extrapolating results to predict performance of new or different vehicles. One of the best applications of the cone, because of its sensitivity, is for spatial characterization of the terrain. For example, Hadas and Shmulewich (1990) use a spectral analysis of cone data to determine the spatial arrangement of soil clods. Ohmiya and Masui (1988) have taken this type of analysis one step further, using three-dimensional graphical representation of the cone data to aid in visualization of the spatial variation of soil strength. The penetrometer has also been very successful in agricultural studies as an indicator of plant growth or root penetration (Taylor et al. 1966, Bowen 1976).

Although the value of the cone penetrometer depends on the type of study, it is no doubt the most universally used and widely accepted index of soil strength for vehicle mobility studies.

Plate sinkage

The plate sinkage test is used to determine the pressure-sinkage relationship (or flotation characteristics) of the soil. The plate sinkage test performed for mobility studies differs from that commonly used in civil engineering for determining bearing capacity. For mobility studies, the area of the plate should be large enough to simulate the contact patch of the tire. (The same plate is also used to predict mobility of tracks; it is not the total area of a track but rather simulates the contact area of the track pads supporting the peak load.) Sometimes a range of plate shapes and sizes are used. The plate penetration equipment can be mounted either on a portable test rig or on an off-road vehicle where it is possible to generate large normal loads. Repetitive loading is used to provide information on terrain response to multiple passes.

The plate sinkage test, along with a shear annulus measurement, is used in a well known terrain characterization apparatus called a bevameter (for Bekker value meter), shown in Figure 2. With a bevameter, plate penetration is used to measure bearing capacity, and the shear annulus (discussed later) is used to determine the shearing characteristics of the soil. Hence, both the normal and shear loading of a vehicle are simulated. These strength parameters (c, ϕ, and K representing shearing behavior and n, k_c, and k_ϕ representing sinkage) are then used in Bekker's analytical model for predicting vehicle performance (Bekker 1969). Karafiath and Nowatzki (1978), however, argue that the fundamental assumptions behind the test method and analysis are not entirely consistent with the tractive behavior of a wheel or track. Wong (1989) gives bevameter results on a range

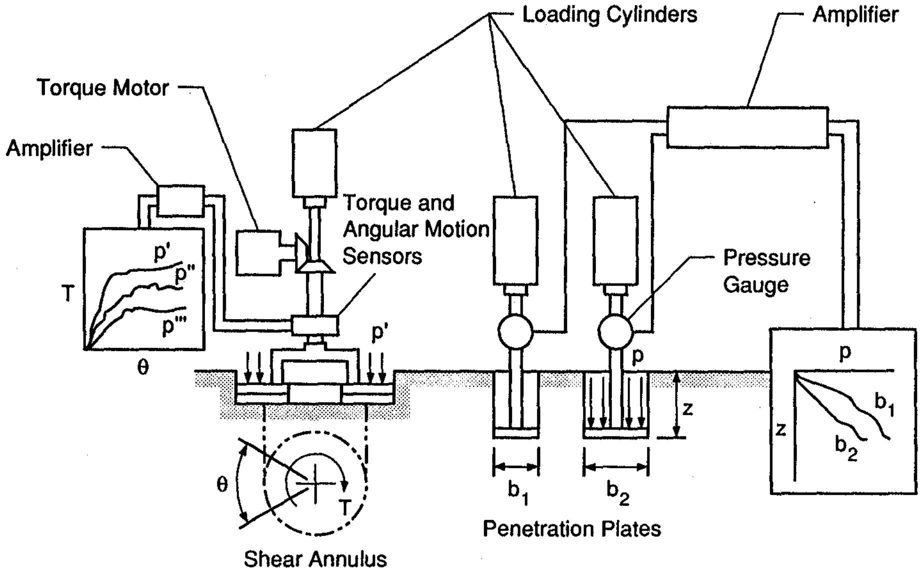


Figure 2. Components of a bevameter (after Bekker 1969).

of terrains including different mineral soils, organic terrain (muskeg), and snow. Two vehicle-mounted bevameters are described in Wong (1989) and Alger (1988).

In situ shear tests

While the penetration techniques mentioned above relate to vehicle sinkage and motion resistance, measurements of the shear strength of soil give information more indicative of tractive performance. Several field methods for assessing the shear strength of soil are summarized briefly below.

Shear vane

The shear vane device is a simple tool designed to measure the shear strength of clays (Fig. 3). The vanes are typically about 70 mm in diameter and 100 mm in height but may vary in size depending on the purpose of the instrument. The instrument is pressed into the soil and then rotated, and the shear strength of the soil is reflected in the torque needed to rotate the device as the soil fails in shear in a cylindrical shape around the vane circumference. Since there is no way to change the load normal to the shear plane, the shear vane is not suitable for frictional soils, but it is handy in silts and clays. Although there is an ASTM standard for laboratory

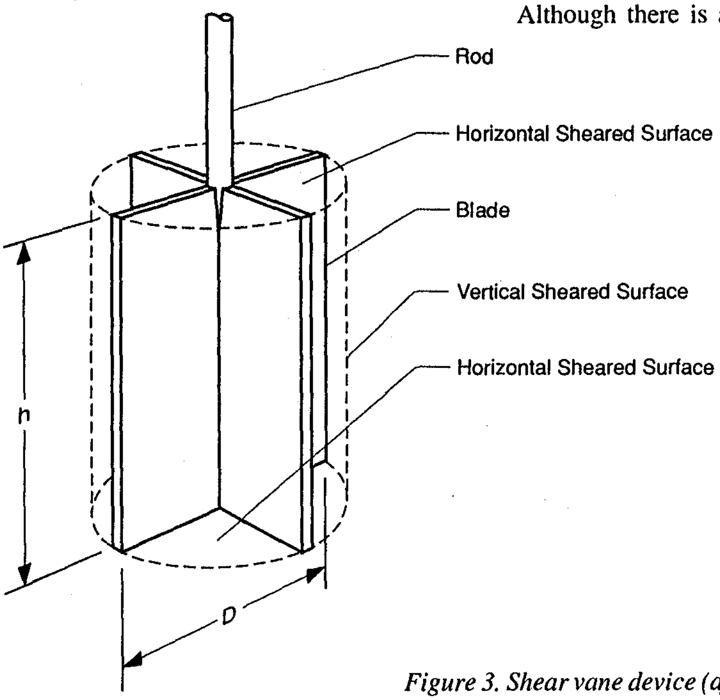


Figure 3. Shear vane device (after Kogure et al. 1988).

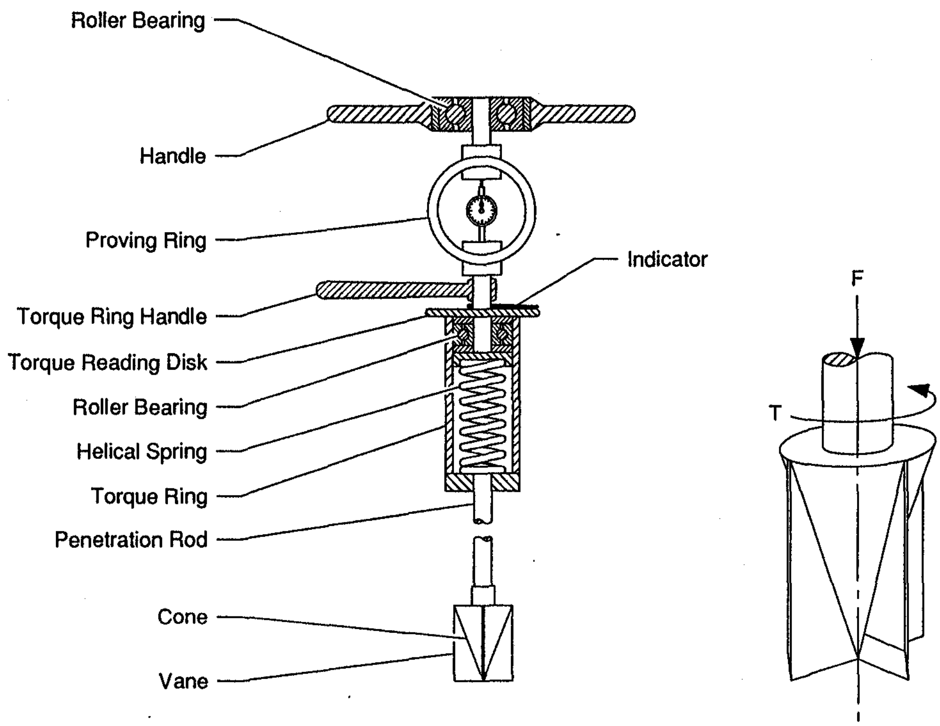


Figure 4. Vane-cone (after Yong and Youssef 1978).

tests using a miniature shear vane (ASTM Standard D 4648-87), no standard exists for the field technique.

Vane-cone

Combining the penetration resistance measurement of the cone penetrometer with the shear strength of the shear vane, a vane-cone penetrometer (Fig. 4) was proposed by Yong et al. (1975). The idea is that the compression and flotation behavior as well as soil shear resistance can be evaluated with one simple and easy-to-use device. The vane-cone is pressed into the soil and then, at a specified depth, is rotated while the depth is held constant. Vehicle mobility prediction equations based on the parameters given by the results of vane-cone measurements are presented by Yong and Youssef (1978). In a soil test bin study on a soft clay, they found that predictions based on the vane-cone were favorable, but additional studies and acceptance of this combination device are yet to come.

Cohron sheargraph

Other types of shear devices apply a shearing force along the surface of the soil. Of this category of instruments, the Cohron sheargraph is the most compact and easy to use. It is hand operated by placing the shear head on the soil using the desired normal load and then applying a shearing force by rotating the device. Both the normal and shear forces are recorded on the drum graph attached to the instrument (Fig. 5). Although the

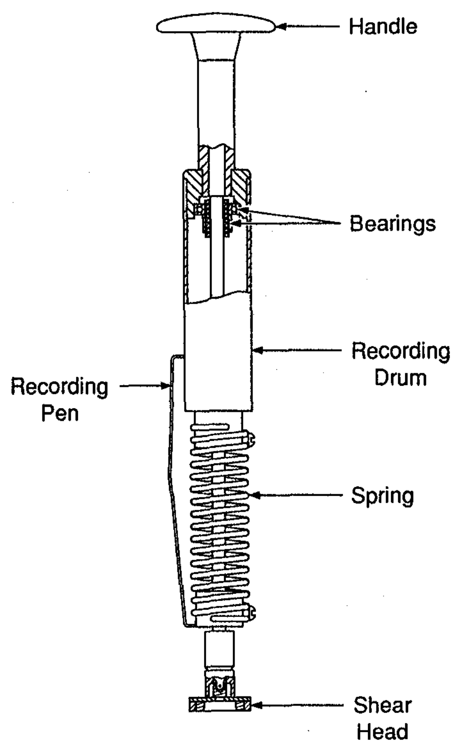


Figure 5. Cohron sheargraph (after Karafiath and Nowatzki 1978).

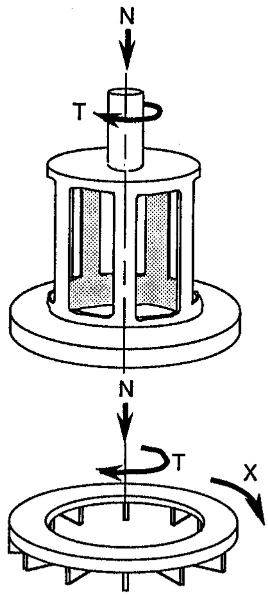


Figure 6. Shear annulus.

sheargraph has been around for many years and is still in use (Flores 1990), it has not become widely accepted. Its light weight and small size make it a handy field instrument, but at the same time the readings are less consistent because of the small area sampled and the sensitivity to operator error. However, Patin (1972) found the Cohron sheargraph to be more consistent than similar techniques (using a spline shear device) and stated that the sheargraph "yielded measurements that were somewhat more indicative of the tire performance than those obtained with the cone penetrometer."

Annular shear ring

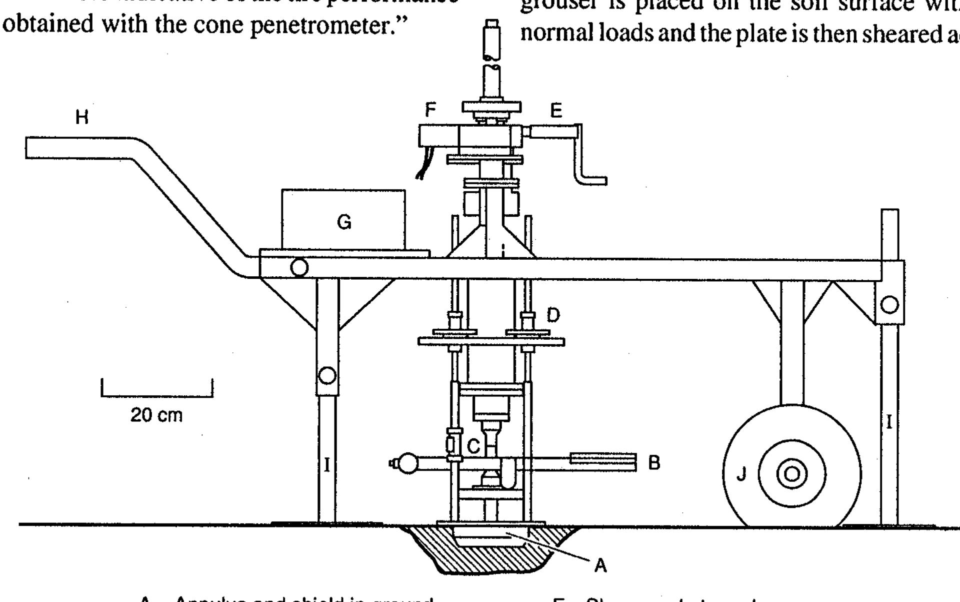
Annular shear tests were proposed by Bekker (1969) and are a part of the bevameter technique of assessing soil strength for mobility prediction (Fig. 2). To assess shear strength, an annular plate is placed on the soil with an applied normal load and rotated at a constant rate. The annular plates can have either a metal or rubber surface as well as grousers (Fig. 6). The test is performed at a range of normal loads to determine the Coulomb shear strength parameters corresponding to the soil/metal or soil/rubber shear. Stafford and Tanner (1982) suggest that more than six different normal loads be used during the field procedure to obtain significant results.

The shear annulus is commonly mounted on an off-road vehicle as part of a bevameter, as described in Wong (1989) and Alger (1988). However, a smaller and simpler set-up, which can be operated by one person (Fig. 7), is described by Stafford and Tanner (1982).

A drawback to the technique is that the failure of the soil beneath the shear ring can occur on a plane oblique to the plane of the annulus ring, so the true normal and shear stress values along the failure plan are unknown (Liston 1973). The development of the oblique failure planes, however, can be avoided by placing a surcharge on the soil around and inside the annular ring (Karafiath and Nowatzki 1978).

Grouser shear plate

A similar concept is the shear plate where a plate or grouser is placed on the soil surface with a range of normal loads and the plate is then sheared across the soil



A - Annulus and shield in ground
B - Loading lever
C - Torque transducer
D - Mechanism for withdrawing shields
E - Reduction gear box and manual drive
F - Shear angle transducer
G - Instrumentation and recorder
H - Lift handles
I - Support legs
J - Transport wheel

Figure 7. Portable shear annulus (after Stafford and Tanner 1982).

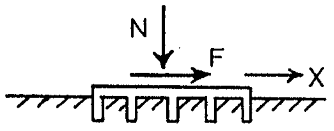


Figure 8. Grouser shear plate.

(Fig 8.). However, rather than a rotational shear, the plate moves across the soil in a linear mode.

Both the annular shear ring and the shear plate may need to be mounted on a heavy portable stand or a vehicle to achieve the necessary vertical load. In addition, the shear plate may need high horizontal forces. A portable test rig that includes a translational shear grouser as well as plate sinkage and cone index capabilities is described in Upadhyaya et al. (1990).

In situ direct shear

The in situ direct shear test essentially duplicates the direct shear test commonly performed in the laboratory. By performing the test in the field, the pretest soil conditions (moisture, density, and texture) remain closer to the actual field conditions, as compared with gathering and removing a sample to be tested in the laboratory. Sample preparation consists of carefully cutting an "undisturbed" sample or excavating the soil so that the shear box can be placed around the soil in situ (Fig. 9). As in the laboratory, the soil is sheared at several applied normal loads. Because of the time-consuming nature of sample preparation, however, usually too few samples are tested so a good sampling of the material is generally not obtained.

Devices reproducing wheel motion

Wheel-shaped devices

To characterize the tractive capacity of the soil accurately, the test device should more closely simulate the motion of a wheel (or track). Thus, a new kind of test rig, where the device acting against the terrain is shaped like a segment of a wheel and acts like a wheel slipping over the soil surface, was proposed by Wasterlund (1990). The simulated wheel is made of a rubber surface over rigid steel and moves in an arc across the soil, as shown in Figure 10. This apparatus has been used to

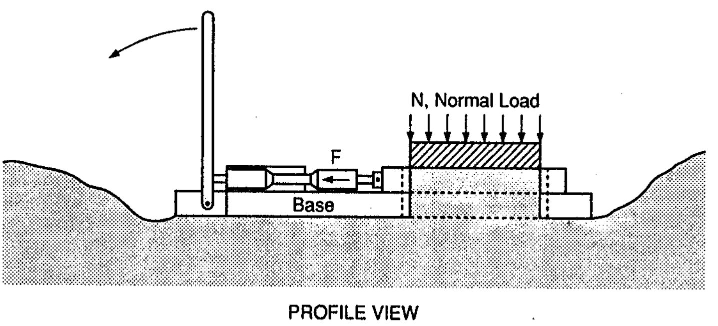


Figure 9. In situ direct shear apparatus.

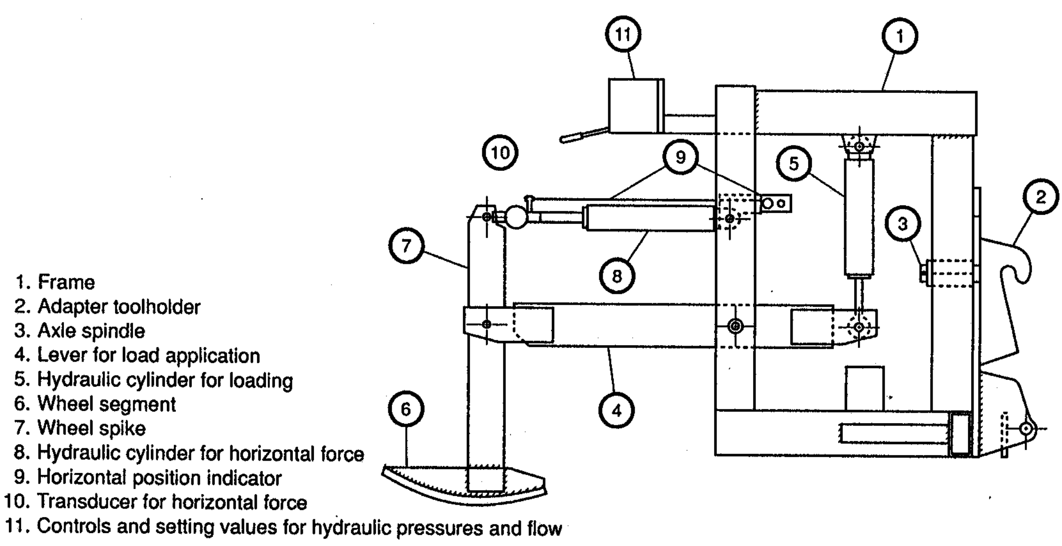


Figure 10. Wheel arc test rig (after Wasterlund 1990).

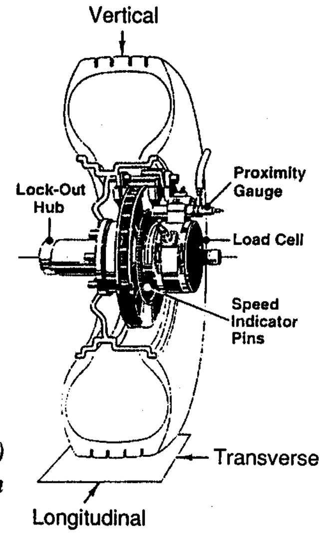
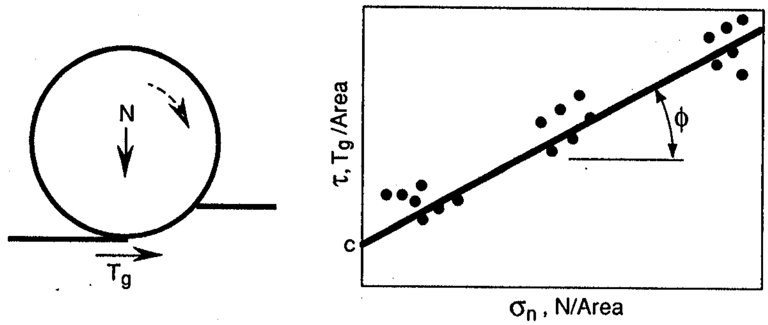


Figure 11. Use of an instrumented wheel to measure (top) tire/terrain interface forces and (bottom) tire/terrain strength parameters (after Shoop 1989, 1992).



characterize the strength of the forest floor to avoid terrain damage from forestry operations.

Instrumented vehicle wheels

A vehicle with instrumented wheels can also be used to assess the strength of the tire–soil system (Shoop 1989, 1992). Triaxial load cells mounted on the wheel axles measure the forces at the tire/soil interface as recorded through the response of the axle (Fig. 11 [top]). During a traction test, the measured longitudinal force is equivalent to the net traction at the wheel. Gross traction (T_g) applied to the soil surface is then estimated by subtracting the motion resistance, and the applied tractive (longitudinal) and vertical forces are converted to stresses by dividing by the tire contact area. Traction tests are performed at a range of applied normal stresses by changing the tire contact area using different inflation pressures. The terrain–tire shear parameters are calculated using a Mohr-Coulomb approach (Figure 11[bottom]); these mobility terrain parameters are used to characterize the soil for mobility purposes and to predict the mobility of other vehicles on the same soil conditions.

Komandi (1990) also calculated soil parameters from vehicle slip-pull curves obtained in the field. He concludes that the Mohr-Coulomb theory is a valid description of the mechanics of the tire/soil interface but for firm soils the internal angle of friction is also dependent on slip velocity.

Comparison of test methods

Several studies have been conducted comparing the results of various strength measurement techniques (Patin 1972, Johnson et al. 1987, Kogure et al. 1988, Shoop 1989). Okello (1991) strongly recommends the use of in situ techniques over laboratory techniques but emphasizes that the size of the device (referring to plate sinkage) should be comparable to the size of the lug or track elements. As expected, there is disagreement between the shear strength values obtained from the different test instruments, primarily because of the magnitude and direction of the applied stress and the rate of deformation.

One of the most comprehensive studies of shear test techniques was published by Stafford and Tanner (1982). They compared six shearing techniques on six different soils, with the results summarized in Table 1. Although results vary with soil type, the vane shear consistently yields the highest values of cohesion, except when used on remolded soils. Similarly, when comparing vane shear, direct shear, and triaxial tests, Kogure et al. (1988) report the vane shear to yield the highest values

Table 1. Comparison of cohesion and friction angle measurements (after Stafford and Tanner 1982).

Soil	Torsional shear Box	Torsional shear Annulus	Direct shear Box	Triaxial test Undrained	Triaxial test Drained	Shear vane
a. Cohesion (kPa)						
1	28.5	39.3	14.8	6.5	17.4	43.3
2	36.3	41.9	54.3	11.1	14.4	54.1
3	81.9	88.6	50.1	33.5	41.9	92.8
4	33.0	36.1	19.9	11.3	15.5	50.3
5	40.4	62.3	28.2	10.3	21.1	38.5
6	1.6	4.2	6.2	4.9	3.1	5.5
b. Friction angle (deg.)						
1	28.5	33.2	33.2	25.4	29.7	—
2	20.2	13.7	21.4	17.3	26.4	—
3	38.1	22.9	24.0	11.3	11.3	—
4	29.0	30.8	34.4	16.9	21.9	—
5	20.5	21.3	8.3	6.0	2.8	—
6	14.8	8.8	31.6	31.8	33.3	—

Soils 1 = sandy clay loam 4 = peat
2 = clay 5 = remolded clay
3 = clay with stone 6 = remolded sand

of shear strength and the direct shear the lowest. Kogure also studied the effects of sample orientation for each of the tests and found the results from the vane shear to be independent of orientation. In studies that have included the (Cohron) sheargraph, summarized in Johnson et al. (1987), the sheargraph was found to yield the highest values of cohesion but not necessarily the highest friction angle. Shoop (1989) compared shear annulus, direct shear, and triaxial tests with terrain strength values calculated from traction tests (on silty sand) and found that the undrained triaxial tests most closely compared with the failure envelope calculated from the forces at the vehicle tire/soil interface (Fig. 12).

Availability

Of the techniques discussed, the sheargraph, shear vane, and cone penetrometer are commercially available through Soiltest, Inc., of Evanston, Ill., or Eijkelkamp, Agrisearch Equipment in The Netherlands (through Sauze Technical Products Corp. of Plattsburgh, N.Y.). The cone penetrometer is also available through the U.S. Army supply system. The Clegg Impact Hammer is available from Lafayette Instrument Company. The in situ direct shear is usually a modification of laboratory direct shear instruments, and the shear plate, shear annulus, and plate sinkage equipment are generally made to specifications. The wheel simulation test rig was custom-built at the Swedish University of Agricultural Sciences in Garpenberg, Sweden. Instrumented wheels and vehicles are custom built by Hodges Transportation of Carson City, Nev.; Testing Services and In-strumentation of Westfield Center, Ohio; DataMotive, Inc., of Reno, Nev.; and the Cold Regions Research and Engineering Laboratory of Hanover, N.H.

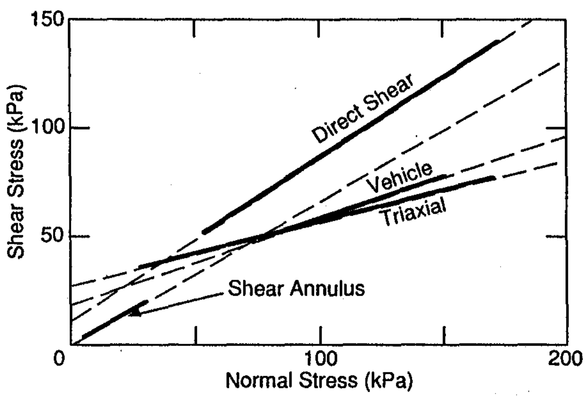


Figure 12. Yield envelopes on silty sand for different test methods (after Shoop 1989).

ORGANIC TERRAIN AND VEGETATION

Organic terrain, also called *muskeg*, is a term used to describe terrain comprising a surface layer of vegetation with a subsurface layer of peat or fossilized plant debris. It includes terrains such as peat bogs, swamps, tundra, and forest floor. The surface of this terrain is composed of a living organic mat of mosses, sedges, and/or grasses, either with or without tree and shrub growth. Underneath this vegetative mat is a mixture of partially decomposed and disintegrated organic material called *peat* or *muck*. To be classified as muskeg, the peat must be over 450 mm thick when undrained or 300 mm when drained and have an ash content less than 80% (Radforth and Brawner 1977). The typical stratigraphy of organic terrain is sketched in Figure 13.

As a rule, peat or muck is highly compressible

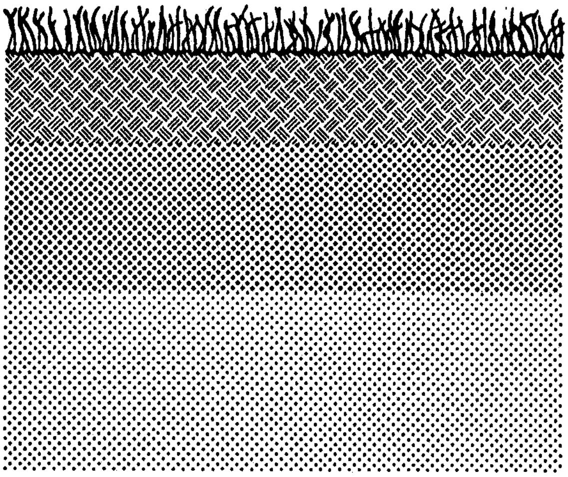


Figure 13. Typical organic terrain (muskeg) profile (after Yong 1985).

compared with most mineral soils; it is characterized by its very high water content and its extremely low bearing capacity (MacFarlane 1958). To a great extent, the trafficability of muskeg depends on the strength of the vegetative mat overlying the soft peat or muck below, and vehicle mobility depends on the success of the vehicle to utilize the strength of the mat effectively without tearing or breakage.

A classification system for muskeg was proposed by Radforth (1952) and compiled into a field guide by MacFarlane (1958). The classification scheme is based on the vegetation, the contained peat/muck, the underlying mineral soil, and the topography. This was integrated with the system of the British Mires Research Group yielding the nine pure vegetative coverage classes given in Table 2. No species identification is necessary; only the qualities of the vegetation are needed, making this classification system suitable for use by engineers or scientists unskilled in plant identification. Since the classes usually occur in combinations, the terrain is designated by combinations of two or three of these class letter designations, starting with the most prominent class. Seven common muskeg classifications are described by Radforth and Evel (1959) in Table 3.

The descriptions and classification of the various types of muskeg offer qualitative indications of the engineering properties of the terrain, particularly with respect to vehicle mobility. For the muskeg classifica-

Table 2. Structural classification of vegetal cover of muskeg (peatland) (integration of British and Canadian systems, from MacFarlane 1958, 1969).

*British Mires Research Group**	*Class symbol*	*Radforth System*			
		Texture	*Stature*	*Form*	*Example*
Trees > 5 m	A	Woody	4.5 m (15 ft) or over	Tree form	Spruce, larch
Trees < 5 m	B	Woody	1.5–4.5 m (5–15 ft) or over	Young or dwarfed tree or bush	Spruce, larch, willow, birch
Shrub habit, 500 mm to 2 m	D	Woody	0.6–1.5 m (2–5 ft)	Tall shrub or very dwarfed tree	Willow, birch, Labrador tea
Shrub habit < 500 mm Creep shrub < 500 mm	E	Woody		Low shrub	Blueberry, laurel
Broad-leaved herbs	G	Nonwoody	Up to 0.6 m (2 ft)	Singly or loose association	Orchid, pitcher plant
Sedge-graminoid habit, 1–3 m a) mats b) hummocks	C	Nonwoody	0.6–1.5 m (2–5 ft)	Tall, grasslike	Grasses
Sedge-graminoid habit, < 1 m a) mats b) hummocks	F	Nonwoody	Up to 0.6 m (2 ft)	Mats, clumps, or patches sometimes touching	Sedges, grasses
Moss habit	I	Nonwoody (soft or velvety)	Up to 100 mm (4 in.)	Often continuous mats, sometimes in hummocks	Mosses
Lichen habit	H	Nonwoody (leathery to crisp)	Up to 100 mm (4 in.)	Mostly continuous mats	Lichens

*Adapted by Radforth.
NOTE: Following classification, observer states percentage of cover class within 20%.

Table 3. Characteristics of seven common muskeg terrains (after Radforth and Evel 1959).

Common formulae	*Associated topographic features*	*Subsurface peat structure*
AE	Irregular peat, plateaus	Coarse-fibrous, woody
AEH	Irregular peat, plateaus, rock enclosures	Woody coarse-fibrous with scattered wood erratics
DFI	Stream banks	Woody particles in nonwoody fine-fibrous
DEI	Ridges, stream banks	Woody particles in nonwoody fine-fibrous
EH	Even peat plateaus, polygons	Woody and nonwoody particles in fibrous
EI	Ridges, mounds	Woody particles in nonwoody fine-fibrous
FI	Hummocks, closed and open ponds, polygons, flats	Amorphous granular, nonwoody fine-fibrous

tions given in Table 3, a corresponding range of vehicle performance parameters (displayed graphically in Figure 14) and desirable vehicle design factors (Fig. 15) were assessed by Radforth and Evel (1959). Other engineering characteristics of each of the muskeg cover classes are given in MacFarlane (1969).

The Swedish Army has also been very successful using plants as indicators to predict trafficability of muskeg. Fridstrand and Persson (1990) analyzed data obtained using cone penetrometer, vane shear, bevameter, and plant identification along with trafficability measurements at two bogs in Sweden, and they found that vegetation was the major factor influencing trafficability.

Many of the techniques used to assess trafficability of soils have also been used on muskeg with varying degrees of success, depending on how the test evokes the strength of the vegetative mat. Since the vegetative mat overlays very soft peat, the degree of vehicle mobility depends on the flotation and traction provided by the

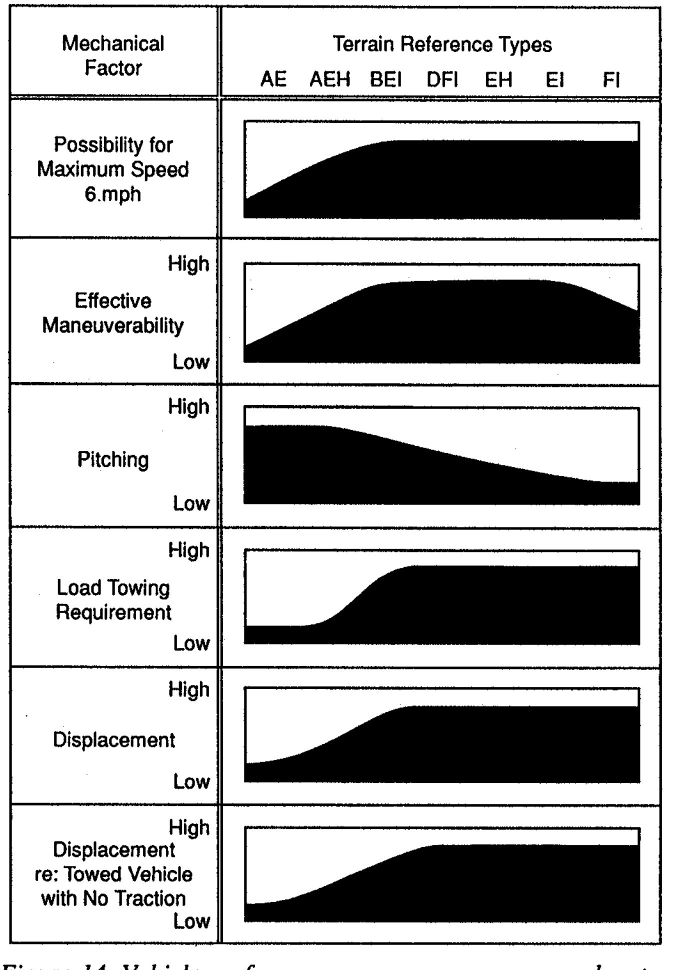


Figure 14. Vehicle performance on seven common muskeg terrains (after Radforth and Evel 1959).

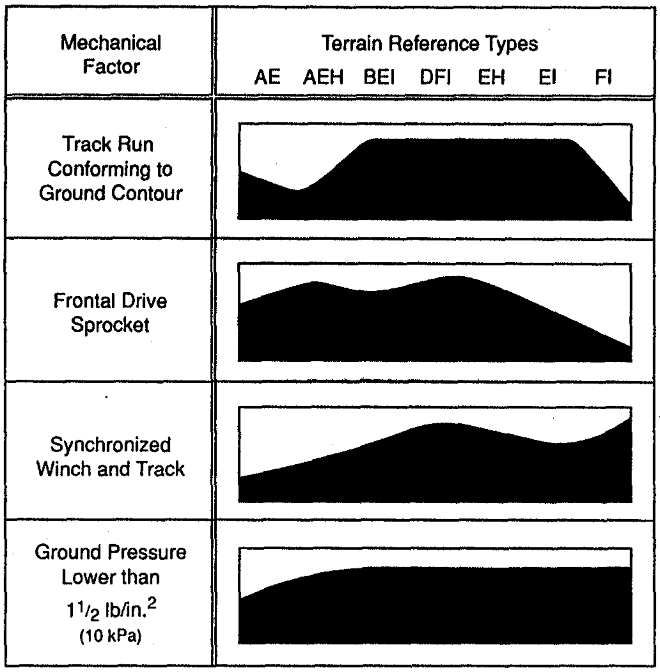


Figure 15. Relative effectiveness of vehicle design parameters on different muskeg terrains (after Radforth and Evel 1959).

mat. In addition, repeated loading of the mat by multiple passes may pump fine-grained muck up onto the mat surface, reducing the traction through slipperiness. The mat's ability to support vehicles is provided by the overall tensile strength of the vegetation and the interlocking stems and roots. Many of the traditional soil strength measurements fail to obtain an adequate measure of the tensile properties of the mat and therefore inadequately characterize the terrain for trafficability. Even so, some success has been reported with the cone penetrometer (U.S. Army 1959), shear vane (Thomson 1960, Irwin and Yong 1980), and bevameter (Wong 1989).

Several instruments have been designed specifically to measure the tensile or tear strength of muskeg and vegetation mats. MacFarlane (1969) describes a muskeg "fluke" consisting of several spikes (Fig. 16) inserted into the vegetation and attached to a cable to which a load is applied. Measurements of the mat tearing strength using the fluke are reported in Table 4. Scholander (1973) measured the tearing strength of several forest

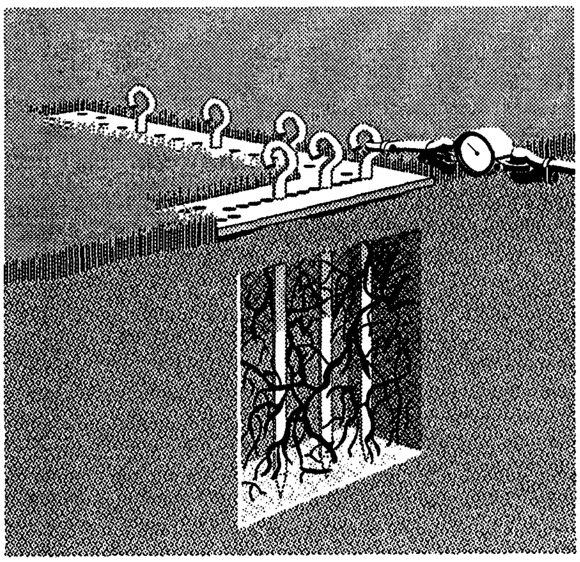


Figure 16. The muskeg fluke (from MacFarlane 1969).

Table 4. Tearing resistance of muskeg measured with the muskeg fluke (after MacFarlane 1969).

Cover formula	Avg shearing force (lb)	Avg shearing force N
FI, wet between EI mounds	2,100	9,341
EI mounds, E ~ I	1,650	7,339
FIE	2,450	10,898
EI mounds E ~ I	1,467	6,525
FI (low, wet area)	2,667	11,863
FI (very wet), dense F	2,483	11,044
EI mounds, dense E	2,788	12,401
IF, I very dense	1,700	7,562
EI mounds, E = I	1,933	8,598
DFI (very wet)	1,950	8,674
FI (very wet)	1,650	7,339
EI mounds, E = I	2,050	9,118
FI, F = I	2,417	10,751
IE hummocks	1,717	7,637
FIE, F = I	2,367	10,528
EI hummocks	2,600	11,565

Table 5. Breaking lengths and yield/rupture ratios from tearing resistance tests on forest soils (from Scholander 1974).

a. Survey of mean values of $S_{breaking}$ (stretch distance) of different types of vegetation and soils.

Vegetation type	*Soil texture*	$S_{breaking}$ *(mm)*
None present	Sand	50–100
Grass	Fine sand, silt	140-220
Dwarf-shrub	Sand	280–330

b. Ratio between yield and rupture limit of some uniform vegetation types.

			Force $F_{yield}/F_{rupture}$		*Extension* $S_{yield}/S_{rupture}$	
Vegetation	*Soil texture*	*No. of observations*	*Mean value*	*Std. error*	*Mean value*	*Std. error*
Grass	Silt	32	0.78	0.02	0.58	0.03
Dwarf-shrub	Sand	22	0.70	0.03	0.53	0.04
Grass	Well moldered peat	35	0.76	0.03	0.51	0.04

soils (vegetation-covered mineral soils) by inserting a vertical plate into the vegetation mat and applying a load by pulling the plate with a vehicle-mounted winch. The results show that the vegetation cover provides three to five times greater tearing resistance than bare soil (sand), and that the tearing resistance varies only moderately throughout the unfrozen part of the year. Tearing resistance varies with soil conditions, but within the same conditions the rupture force is a constant function of the breaking length. This breaking length can be compared with the wheel slip as a percentage of the contact length to determine if the vehicle will tear the mat. Some of the measured breaking lengths and yield/rupture ratios are given in Table 5. Scholander (1973) also observes that the vegetation fails first on the surface, in the pulling direction, with the final rupture occurring as a tensile failure of the root mat at the sides and bottom. This is the same failure progression observed by Niemi and Bayer (1970) from tear resistance tests on muskeg using the instruments shown in Figure 17. Bjorkhem et al. (1975) used plate sinkage tests to evaluate the effects of roots on compressive strength (or bearing), finding that even though the modulus values are nearly the same, the ultimate strength of the root–soil system was 70% greater than for soils without roots.

In a summary report describing several years of research for forest operations on peat lands in Finland, Rummukainen (1984), Saarilahti (1982), and Saarilahti

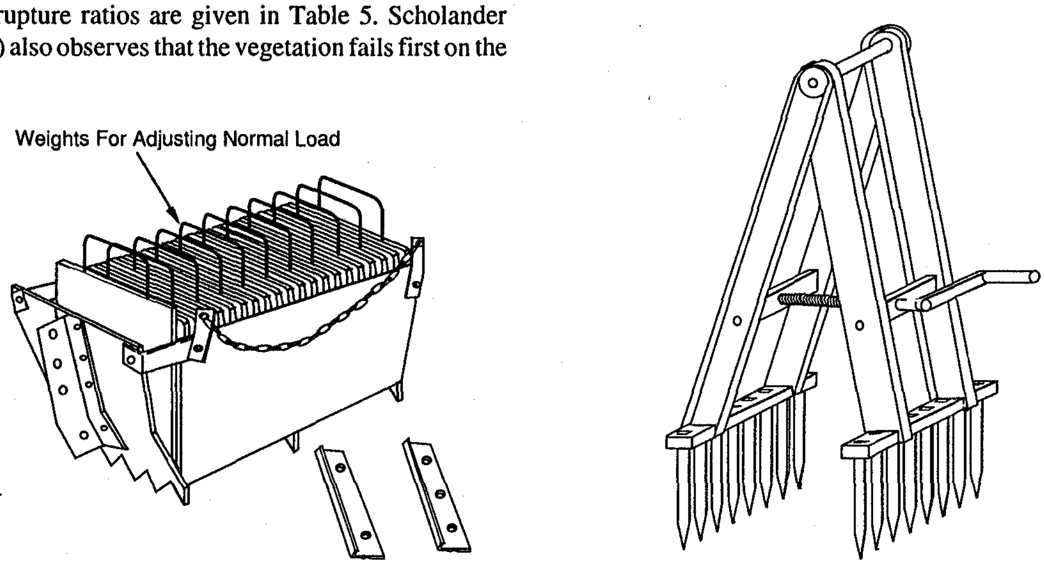


Figure 17. Instruments used by Niemi and Bayer (1970) to measure (a) shear resistance and (b) tensile strength of the vegetation mat.

Mean vane shear strength (kN/m²)*	Surface wetness class† 1	2	3	4	5
	Index of trafficability				
20.0–	1	3	6	8	9
17.5–19.9	2	4	7	8	9
15.0–17.4	3	5	7	8	9
12.5–14.9	4	6	7	9	9
0.0–12.4	5	7	7	9	9

* Surface wetness classes:
1–Dry, boot sole dry
2–Normal, boot sole wet
3–Wet, water over boot sole
4–Very wet, water rises on boot upper
5–Extremely wet, water rises over boot upper

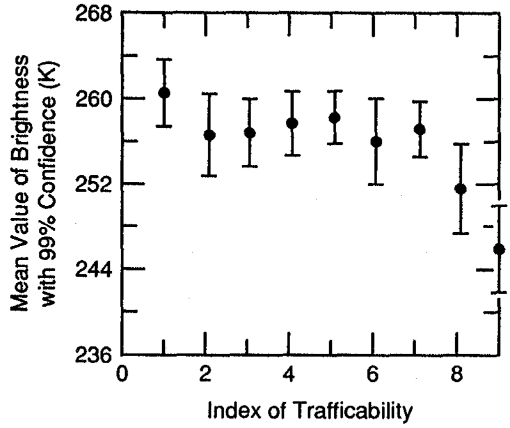


Figure 18. Basis of trafficability index (top) and brightness temperature by trafficability class (bottom) (after Saarilahti 1982, Rummukainen 1984).

and Tiuri (1981) suggest that the traditional strength measurements are singular values, while continuous information is more appropriate for estimating vehicle mobility. They warn that indicator plants may not be reliable as they are adaptable to variations in growing conditions and competition from other plants. Based on evaluations of peat lands for trafficability using penetrometers, vane shears, and bevameters, as well as radar techniques to assess peat depth and water content, they note that the strength of peat is directly related to the moisture content and depth. A trafficability index based on vane shear strength and surface wetness class was developed and related to radiometer brightness levels, as shown in Figure 18. Thus, radio wave techniques are proposed as an alternative to the more limited point-wise measurements (cone, vane, and bevameter) for evaluating peat lands for vehicle operations.

Other factors commonly influencing mobility on muskeg terrain are associated topographic features, seasonal ice forms, and ice thickness. Small-scale terrain roughness features, such as hummocks, polygons, ridges, ponds, and bars, are included in the topographic classifications of muskeg shown in Table 6 (MacFarlane 1958), and seasonal ice forms are characterized based on their effect on mobility, as shown in Figure 19 (Radforth and Evel 1959). Some of these are not large enough or of an areal extent to stop a vehicle, but they may slow vehicle progress considerably and cause wear and tear to vehicle components. Although ice forms may impede vehicle travel, frozen peat lands are substantially stronger than when unfrozen. The compressive strength of frozen peat can be 350 to 400% higher than unfrozen peat depending on the water and vegetation content (Rummukainen 1984). Generally, 0.2 to 0.3 m of frost on wet peat lands will bear most heavy equipment (MacFarlane 1969), and less frost will bear weight

Table 6. Muskeg topographic classifications (after MacFarlane 1958).

Contour type	*Feature*	*Description*
a	Hummock	Includes "tussock," has tufted top, usually vertical sides, occurring in patches, several to numerous
b	Mound	Rounded top, often elliptic or crescent-shaped in plane view
c	Ridge	Similar to mound but extended, often irregular and numerous; vegetation often coarser on one side
d	Rock gravel plain	Extensive exposed areas
e	Gravel bar	Eskers and old beaches (elevated)
f	Rock enclosure	Grouped boulders overgrown with organic deposit
g	Exposed boulder	Visible boulder interrupting organic deposit
h	Hidden boulder	Single boulder overgrown with organic deposit
i	Peat plateau (even)	Usually extensive and involving sudden elevation
j	Peat plateau (irregular)	Often wooded, localized and much contorted
k	Closed pond	Filled with organic debris, often with living coverage
l	Open pond	Water rises above organic debris
m	Pond or lake margin (abrupt)	
n	Pond or lake margin (sloped)	
o	Free polygon	Forming a rimmed depression
p	Joined polygon	Formed by a system of banked clefts in the organic deposit

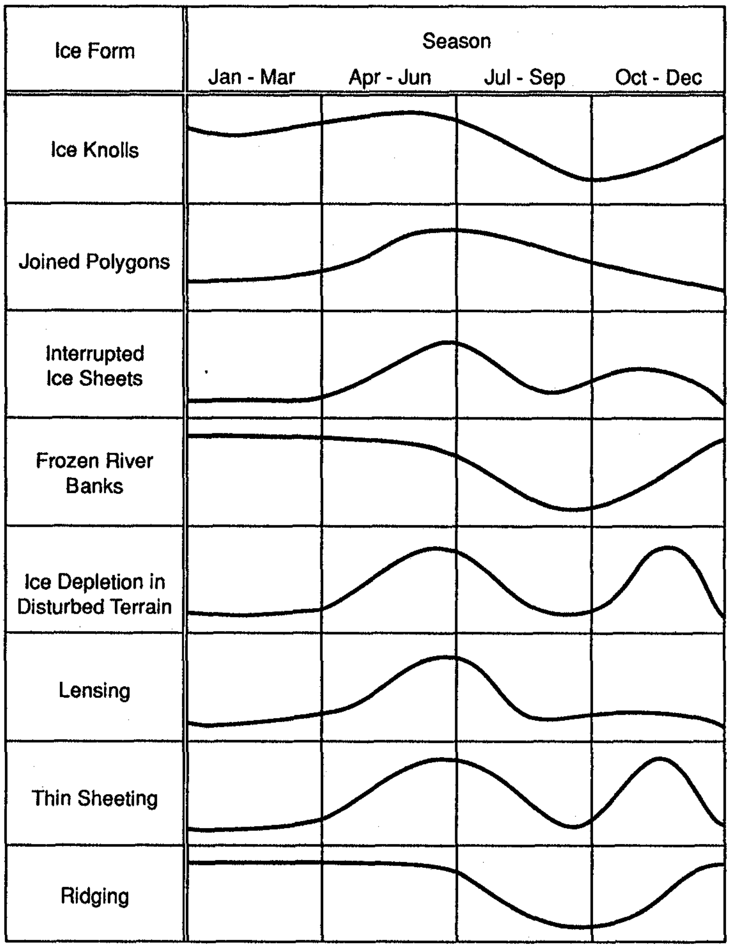


Figure 19. Seasonal influence of different ice forms on mobility (after Radforth and Evel 1959).

Table 7. Bearing strength of frozen peat (after Rummakainen 1984, Hakkarainen 1949).

Thickness (m) of frozen peat layer		
Dry top peat layer	*Wet top peat layer*	*Bearing capacity*
0.10	0.05	Will bear a horse
0.15–0.20	0.10	Will bear 6-t horse sled traffic
0.20–0.35	0.15–0.25	Will bear empty 4-t truck
0.35–0.50	0.25–0.40	Will bear 10-t truck traffic

according to the guidelines (Table 7) provided by Hakkarainen (1949).

Vehicle traffic can also adversely affect the vegetation and the sensitive environment typical of organic terrains. Plant damage causes losses in forestry operations, significant changes in drainage patterns, and associated erosion. In permafrost areas, changes in the vegetation cover alter its thermal characteristics, resulting in thermokarsts and changes in permafrost occurrence. These and other environmental aspects are more thoroughly presented in Radforth and Brawner (1977).

SNOW COVER

There are a variety of techniques for characterizing snow for vehicle mobility or tire traction testing. Snow surfaces that are used for testing are either natural or groomed and vary widely in strength and texture. In some ways, the methodology of characterizing snow is similar to that for soil. Grain size, structure, metamorphic state, temperature, density, free water content, hardness, and strength are measured or described at each significant layer within the snow pack. Since some of the techniques used are also used on soil, the following is a summary of the techniques or aspects unique to snow. A more extensive summary of snow characterization techniques for mobility and snow pavements is presented in Shoop and Alger (1991) and Abele (1990) and classification of seasonal snow cover in Colbeck et al. (1990).

Unique aspects of snow

The size and shape of the ice grains that make up a snowpack have a marked influence on the mechanical behavior of the snowpack as a whole. Large rounded crystals tend to roll past each other, while small angular crystals tend to pack tightly together when loaded. Crystal size and shape are generally documented using a magnifying glass or hand lens and a measurement grid. A comprehensive guide for classification of snow crystals is given in Colbeck (1986) and Colbeck et al. (1990).

Because snow exists close to its melting point, the temperature of the snow environment is extremely important. Temperature can be measured by use of a simple thermometer or with arrays of thermocouples or thermistors. The temperatures are normally measured in a profile through the thickness of the snow pack. Temperature can be used to estimate the probable "wetness" of the snow and, when coupled with a density measurement, can also give a very crude estimate of strength. When working with snow, the air temperature and snow temperature should always be measured. If the snow is deep or if temperature gradients exist within the snow (i.e. the air or ground temperature is significantly different from the snow temperature), a profile of snow temperature measurements is required. For shallow (uniform) snow, a temperature measurement at 25 mm and at the snow/ground interface is sufficient.

The texture and structure of a snow cover are continually changing. Because a fallen snowflake is in a physically unstable form on the ground, it changes its shape with time and is strongly influenced by temperature gradients. Typical stages of snow metamorphism are shown in Figure 20 (Colbeck 1987). Metamorphism affects the shape, size, and bonding of the crystals and therefore the strength characteristics of the snow cover and how it will react when trafficked. Freeze–thaw cycling, for instance, can cause ice lenses to form, markedly increasing the strength of the snowpack in a very short period of time.

Even when temperatures are below freezing, the snow mass may contain some free or liquid water and, because of the melting of the snow grains when heated, the free water content measurement is much different from the standard soil water content measurement. An estimate of whether water is present can be made using visual observations such as squeezing and forming the snow or by chemical indicators that change color when in contact with liquid water. The quantitative measure of liquid water content was historically determined using either freezing or melting calorimetry, which require a good deal of time and careful effort and are

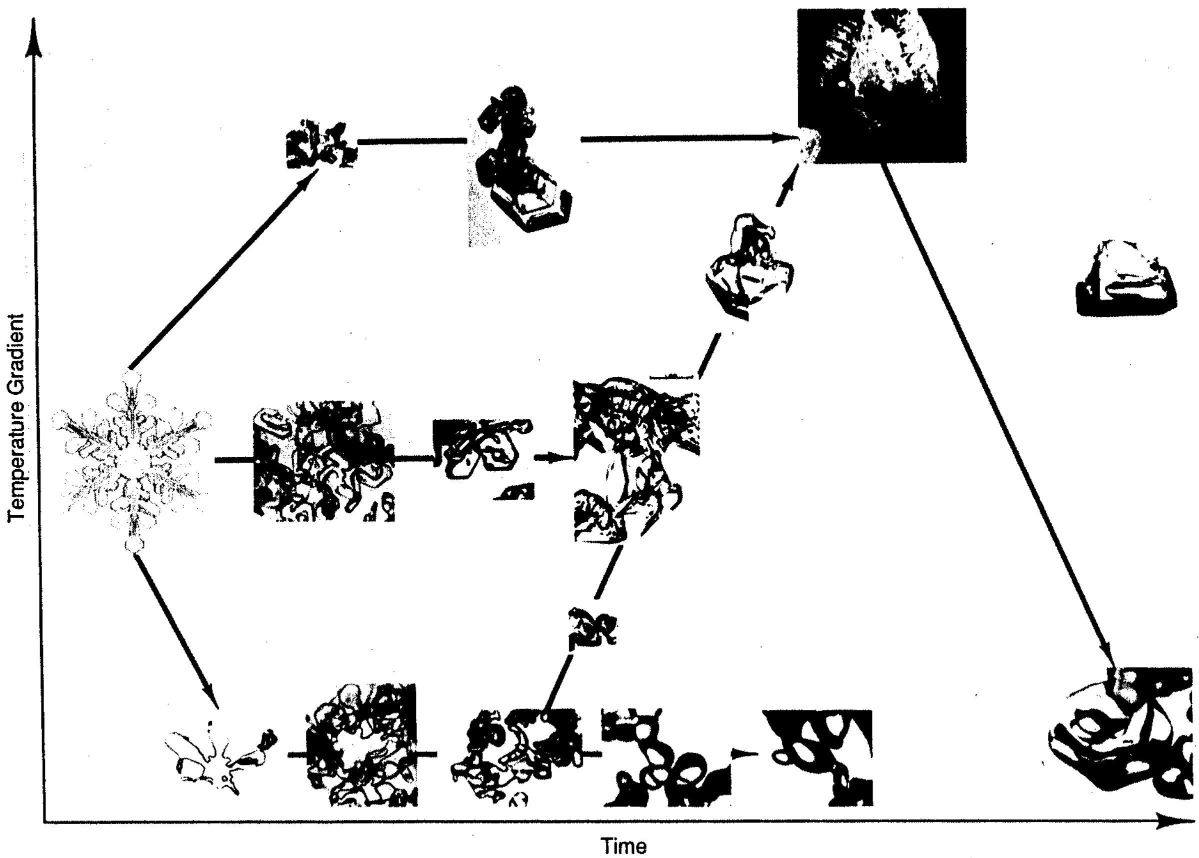


Figure 20. Metamorphosis of snow crystals with temperature and time (after Colbeck 1987).

therefore not desirable for field use. A more recent advancement in liquid water measurement is a capacitance meter that is accurate and easily operated. This gauge consists of a plate that is placed on or in the snow and a small meter that is used to read out the capacitance. By taking a reading in the air and one on the snow surface, the free water content can be determined. This method is becoming increasingly more popular since it does not require any special fluids or bulky equipment and the gauge can easily be carried in a back pack. Boyne and Fisk (1990) compare these three methods of moisture measurement in snow (alcohol calorimetry, freezing calorimetry, and capacitance).

Snow density is measured in much the same way as soil density, by collecting a sample of a known volume and weighing it.

Snow strength indices

The methods presented below are a summary of field methods used for quickly assessing the strength of a snow cover. More sophisticated snow strength and index property measurements are given in a review of snow mechanics by Shapiro et al. (1993).

Bevameter and drop cone

All of the strength measurement techniques used in soils have been tried on snow with varying degrees of success. The most common of the soil strength characterization techniques that are also applied to snow are the bevameter and the drop cone. The bevameter was adequately covered above and its use on snow is discussed in more detail by Alger (1988), Alger and Osborne (1989), and Wong (1989). The drop cone, however, is slightly different from that used on soils; it is sometimes referred to as a snow compaction gauge. The snow compaction gauge shown in Figure 21, built by Smithers Scientific Services, Inc., of Akron, Ohio, is similar to a soil drop cone except that the cone has been rounded. The 220-g (7.75-oz) cone is dropped from a height of 219 mm (8.5 in.). The penetration is a result of vertical and horizontal compaction and shear and indicates the compaction resistance of the snow cover. The penetration distance is converted to compaction numbers using the standardized scale shown in Table 8.

Table 8. CTI snow compaction gauge values (after SAE 1985).

Surface description	*CTI compaction range*
Steel	100
Ice	93 – 98
Extra hard hard-pack snow	84 – 93
Standard medium hard-pack snow	70 – 84
Soft-pack or loose-pack snow	50 – 70
Virgin snow – No rating: Use depth and moisture content	–
Water	1

Rammsonde

The rammsonde is similar to the cone penetrometer except the standard ramm cone is much larger in size and is driven into the snow using a drop hammer (Fig. 22). Generally a complete ramm set-up will have two different sized hammers along with a hammer slide and

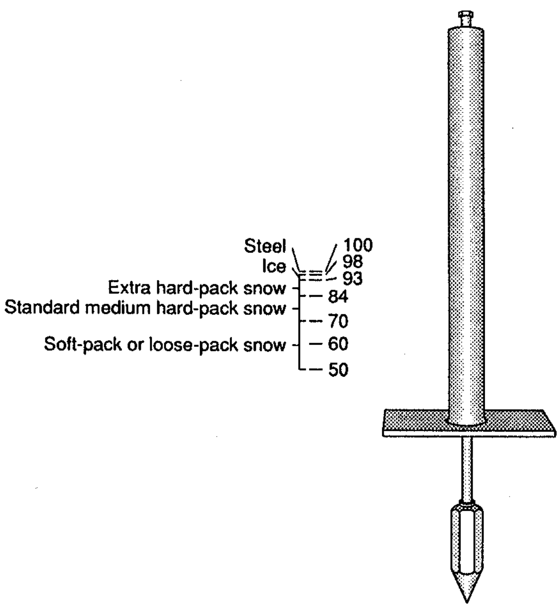


Figure 21. Snow compaction gauge, also called a drop cone (after SAE 1985).

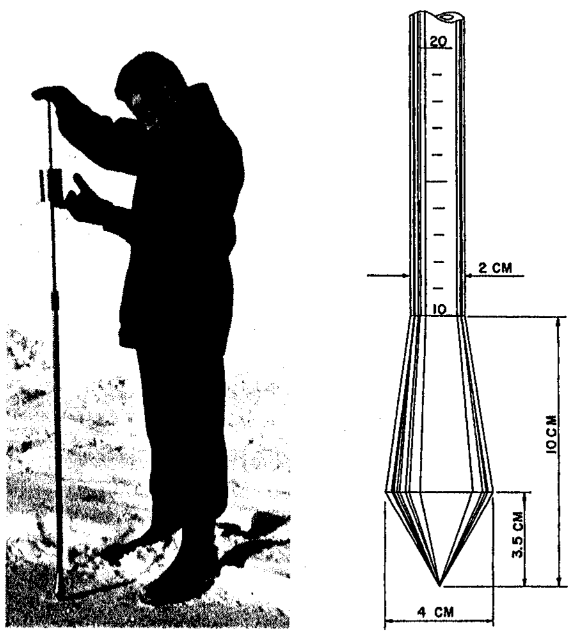


Figure 22. Rammsonde penetrometer (after Abele 1990).

several rod extensions for use in deep snowpacks. To use the rammsonde, the cone is placed on the snow surface and the slide hammer is dropped from a measured height. The penetration of the cone is measured and the process is repeated until the ramm has penetrated the entire depth of the snow pack (or to whatever depth is desired). This instrument has been most successful in deep packs such as avalanche zones and in the Arctic and Antarctic to obtain hardness profiles through deep layers of snow. Correlations between the rammsonde and several other snow properties and strength measurements are presented in Abele (1990). Use of data from a rammsonde for vehicle performance prediction is described in Wong (1992).

Canadian hardness gauge

The Canadian hardness gauge (and similarly, the CRREL hardness gauge) measures resistance to penetration with small plates designed to be carried in a pack in the field. Its major use has been in the area of avalanche prediction; it is best used in hard virgin snow. The plates are various sizes, and the size used depends on the strength of the snow cover. The plate is pushed into the snow either horizontally or vertically, depending on the purpose of the test, and the resistance to penetration registers on a gauge built into the instrument handle. Hardness is generally measured at each of the snow layers within the cover.

Manual snow hardness classification

Snow hardness can also be classified manually, without the aid of gauges or instruments, as described in the Swedish Terrain Classification System for Forestry Work (Swedish Forest Operations Institute 1992) and CRREL Instructional Manual 1 (CRREL 1962). The hardness is tested and classified by the ease of pushing a fist, outstretched hand, finger, pencil, or knife into the snow. The hardness is determined along the profile of a snow cover; the overall hardness of the cover depends on the percentages of each classification present. The test technique and hardness classifications are diagrammed in Figure 23 and are roughly correlated with values from the hardness gauge, as indicated on the figure.

Commercial tire traction testing on snow

To assess the tractive performance of different tire designs on snow, the tire and automotive companies standardized the snow with regard to the tractive performance of a Standard Reference Test Tire (SRTT) or Snow Monitoring Tire (SMT). The snow test section is prepared by tilling, grooming, and compacting as necessary to provide a specified tractive coefficient using the SRTT as outlined in SAE Standard J1466 (SAE 1985). If the SRTT performs within the specified range, the snow is considered adequate for comparing the traction of other tires. Each tire is tested several times

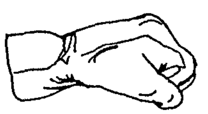
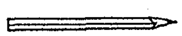
Testing snow hardness The hardness class is based on which of the following can easily be pushed into the snow.		Hardness class	Corresponding hardness gauge reading (g/cm²)
Closed fist covered with glove		Very soft	0–500
Flat extended hand with glove		Soft	
Extended glove-covered index finger		Medium hard	500–2500
Pencil		Hard	2500–5500
Knife		Very hard	>5500

Figure 23. Snow hardness characterization using manual techniques and hardness gauge (after CRREL 1962, Swedish Forest Operations Institute 1992).

and on different dates throughout the winter. On a given test date, the SRTT is tested many times throughout the day (every third tire) to be assured that the snow is continually meeting the standard traction criteria (Shoop et al. 1993).

OTHER FACTORS AFFECTING MOBILITY

Aside from the strength of the substrate, other terrain factors influencing vehicle mobility include vegetation, obstacles, terrain profile (micro relief), water courses, and slopes. Any of these factors may change with time due to natural conditions such as rainfall or snowmelt or man-made conditions such as farming or construction.

In general, the vehicle and driver respond to those factors that absorb energy (by increasing motion resistance, inducing drag, reducing traction, or activating the vehicle suspension), thus reducing or eliminating motion. Grabau* groups these terrain factors into three categories based on how they affect vehicle operation:

- those dealing with surface geometry (small- and large-scale surface irregularities including obstacles)
- those that produce drag on the vehicle (vegetation and shallow water)
- those dealing with the supporting material or substrate (discussed in detail earlier).

Surface geometry affects vehicle mobility at a range of scales from millimeter-sized pebbles on a road to vast changes in the slope angle and orientation of the land. All of these scales can occur at the same location, such as a gravel-covered, washboard road on a slope. One of the most important considerations in assessing the effects of surface geometry is how the amplitude and frequency of the surface irregularities excite the vehicle suspension system. Small-scale surface roughness, such as gravel on a road, may do little more than cause tire noise, but intermediate terrain roughness of tilled farm land or a washboard road may severely reduce the speed and effectiveness of the vehicle operation, affecting the driver and cargo to such an extent as to make the traverse intolerable. Other surface irregularities (such as streams, ditches, large boulders, mounds, and pits) create obstacles to vehicle passage because of incompatibility with the shape of the vehicle: the vehicle "hangs up" on a steep bank or "bottoms out" on a protruding rock.* These features can slow the motion of the vehicle, stop progress entirely, or delay movement by the additional time required to avoid the obstacle.

Vegetation can fall within both geometrical effects and drag-inducing effects. Smaller vegetation causes additional frictional resistance or drag, impeding vehicle movement and in extreme cases actually stopping vehicle motion. On the other hand, vegetation can also provide flotation and traction, supporting vehicles in very wet and soft ground environments not otherwise trafficable, such as bogs or wet forest floor. In these cases it is very important to limit the breakage of the vegetative mat (as discussed in *Organic Terrain and Vegetation* above). Larger vegetation presents obstacles to vehicular movement and limits visibility. This kind of impediment is often characterized by trunk and stem diameter, spacing, and branching frequency. Similarly, boulders can create obstacles and/or provide reinforcement to otherwise weak terrain material (such as wet soil).

Nearly all of these factors are subject to changes with time: daily, seasonally, annually, or over many years. Temporal changes occur in nearly all of the terrain-related factors such as soil moisture and density, plant growth, stream flow, runoff, water depth, stream current velocity, freezing and thawing of ground surfaces and water bodies, and accumulation of snow and ice. For these reasons, a mobility prediction scheme must take climatic data into account. In addition to natural changes in terrain, human intervention in the form of construction or agricultural practices can also change terrain conditions (such as altering water drainage patterns) very quickly.

A good overview of these types of parameters and how they influence mobility can be found in Koeppel and Grabau (1987). An example of how these factors are included in terrain-based mobility prediction models is documented in U.S. Army (1968) and Turnage and Smith (1983). Currently, these types of terrain classification schemes are incorporated into GIS (Geographic Information Systems)-based mobility prediction schemes (Edmark et al. 1990, Fridstrand and Persson 1990, U.S. Army 1992). Similar schemes of terrain classification are used in forestry to plan forest operations and costs. Examples of forestry terrain classification systems are presented in Swedish Forest Operations Institute (1992) and, from Norway, Samset (1975).

Because of the great spatial and temporal variation in the parameters affecting mobility, it is logical to incorporate a statistical representation of the variability into any mobility prediction model. This type of probabilistic approach is necessarily a current area of research in the advancement of mobility prediction. A probabilistic approach is needed for both the descriptive input parameters, such as the statistical distribution of cone penetration data (Kogure et al. 1985, Heiming 1987), as well as the predictive end results such as vehicle speed made good (Lessem et al. 1992). Therefore, while in essence the mobility model may be deterministic for a specific vehicle over a specified terrain, in reality the terrain

* W.E. Grabau, personal communication, 1992.

input is considered as an average value representing a terrain "unit" with specified variability, and thus the operational use of the model generates a range of vehicle performance that can be expected over the variable terrain.

LITERATURE CITED

Abele, G. (1990) Snow roads and runways. USA Cold Regions Research and Engineering Laboratory, Monograph 90-3.

Alger, R.G. (1988) Shear and compressive strength measurements of snow using the bevameter. In *Proceedings of the 1st International Conference on Snow Engineering, Santa Barbara, Calif., July,* USA Cold Regions Research and Engineering Laboratory, Special Report 89-6.

Alger, R.G. and M.D. Osborne (1989) Snow characterization field data collection results. Final report to Department of the Army, Contract No. DACA89-85-K-0002.

Alkire, B.D. and L. Winters (1986) Soil strength recovery using a Clegg impact device. In *Proceedings of the 4th International Conference on Cold Regions Engineering, Anchorage, Alaska, February,* p. 155–166.

ASAE (1985) Soil cone penetrometer. American Society of Agricultural Engineers, Standard ASAE S313.2.

Ayers, P.D. and J.V. Perumpral (1982) Moisture and density effect on cone index. *Transactions of the ASAE,* **25**(5): 1169–1172.

Bekker, M.G. (1969) *Introduction to Terrain-Vehicle Systems.* Ann Arbor, Mich.: University of Michigan Press.

Bjorkhem, U., G. Lundeberg and J. Scholander (1975) Root distribution and compressive strength in forest soils, Root mapping and plate loading tests in thinning-stage stands of Norway spruce. Swedish Royal College of Forestry, Depts. of Forest Ecology and Forest Soils, Research Notes No. 22 (in Swedish with English summary).

Bowen, H.D. (1976) Correlation of penetrometer cone index with root impedance. ASAE Paper No. 76-1516. St. Joseph, Mich.: American Society of Agricultural Engineers.

Boyne, H.S. and D.J. Fisk (1990) A laboratory comparison of field techniques for measurement of the liquid water fraction of snow. USA Cold Regions Research and Engineering Laboratory, Special Report 90-3.

Chancellor, W. (1993) Soil physical properties. Advances in Soil Dynamics Monograph Series, Vol. I, American Society of Agricultural Engineers, ASAE Monograph, in press.

Colbeck, S.C. (1986) Classification of seasonal snow cover crystals. *Water Resources Research,* **22**(9): 59S–70S.

Colbeck, S.C. (1987) Snow metamorphism and classification. In *Seasonal Snowcovers: Physics, Chemistry, Hydrology,* H.G. Jones and W.J. Orville-Thomas (eds.). Dordrecht, The Netherlands: D. Reidel Publishing Co., p. 1–35.

Colbeck, S.C., E. Akitaya, R. Armstrong, H. Gubler, J. Lafeuille, K. Lied, D. McClung and E. Morris (1990) International classification for seasonal snow on the ground. Technical Report MP 2794, issued by the International Committee on Snow and Ice, International Association of Scientific Hydrology, and International Glaciological Society. Boulder: University of Colorado, World Data Center for Glaciology.

Collins, J.G. (1971) Forecasting trafficability of soils. Technical Memo 3-331, Vicksburg, Miss.: USA Corps of Engineers Waterways Experiment Station.

CRREL (1962) *Instructions for Making and Recording Snow Observations.* CRREL Instruction Manual 1. Hanover, N.H.: USA Cold Regions Research and Engineering Laboratory.

Edmark, P., K. Fridstrand and M. Svantesson (1990) Cross country trafficability assessment with a GIS. In *Proceedings of the 3rd Scandinavian Research Conference on Geographic Information Systems, Helsingör, Denmark, November.*

Flores, J.A. (1990) A field method to determine slip and compaction in a work day. ASAE paper from ASAE conference, Columbus, Ohio, June.

Fridstrand, K. and J.F. Persson (1990) Framkomlighet i övre Norrland. Utveckling och utvärdering av framkomlighetsmodell (A model for cross-country mobility). FOA Report C 20819-2.6 (2.7), Sundbyberg, Sweden: National Defence Research Establishment.

Godwin, R.J., N.L. Warner and D.L.O. Smith (1991) The development of dynamic drop-cone device for the assessment of soil strength and the effects of machinery traffic. *Journal of Agricultural Engineering Research,* **48**(2): 123–131.

Hadas, A. and I. Shmulewich (1990) Spectral analysis of cone penetrometer data for detecting spatial arrangement of soil clods. *Soil and Tillage Research,* **18**: 47–62.

Hakkarainen, A. (1949) Routa Talviteiden rakentajana. Metsatehon tiedoitus 29 (in Finnish).

Heiming, G.W. (1987) Statistical procedures for evaluation of terrain measuring data. In *Proceedings of the 9th Conference of the International Society for Terrain-Vehicle Systems (ISTVS), Barcelona, Spain,* p. 143–151.

Hettiaratchi, D.R.P. and Y. Liang (1987) Nomograms for the estimation of soil strength from indentation tests. *Journal of Terramechanics,* **24**(3): 187–198.

Irwin, G.J. and R.N. Yong (1980) Demonstration of a

portable device for predicting vehicle tractive performance in snow. *Journal of Terramechanics*, **17**(4): 197–206.
Johnson, C.E., R.D. Grisso, T.A. Nichols and A.C. Bailey (1987) Shear measurement for agricultural soils—a review. *Transactions of the ASAE*, **30**(4): 935–938.
Karafiath, L.L, and E.A. Nowatzki (1978) *Soil Mechanics for Off-Road Vehicle Engineering*. Clausthal, Germany: Trans Tech Publications.
Koeppel, W. and W. Grabau (1987) Terrain description for mobility prediction, In *Proceedings of the 9th International Conference of ISTVS, Barcelona, Spain*, **I**: 160–175.
Kogure, K., Y. Ohira, and H. Yamaguchi (1985) Basic study of the probabilistic approach to prediction of soil trafficability—statistical characteristics of cone-index, *Journal of Terramechanics*, **22**(3): 147–156.
Kogure, K., H. Yamaguchi and Y. Ohira (1988) Comparison of strength and soil thrust characteristics among different soil shear tests. *Journal of Terramechanics*, **25**(3): 201–222.
Komandi, G. (1990) Establishment of soil-mechanical parameters which determine traction on deforming soil, *Journal of Terramechanics*, **27**(2): 115–124.
Lessem, A.S., R.B. Ahlvin and G.L. Mason (1992) Stochastic mobility forecasts for military vehicles. In *Proceedings of the North American Conference of ISTVS, Sacramento, California*, WES Technical Report GL-92-11.
Liston, R.A. (1973) The combined normal and tangential loading of soil. Ph.D. thesis, Michigan Technical University, Houghton, Mich.
MacFarlane, I.C. (1958) Guide to a field description of muskeg. Associate Committee on Soil and Snow Mechanics, Technical Memorandum 44. Ottawa: Canadian National Research Council.
MacFarlane, I.C. (ed.) (1969) *Muskeg Engineering Handbook*. Toronto: University of Toronto Press.
Mathur, T.S. and G.T. Coghlan (1987) Use of the Clegg impact tester in managing and designing aggregate-surfaced roads. In *Proceedings of the 4th International Conference on Low-Volume Roads, Ithaca, N.Y., August*, p. 232–236.
McKyes, E. (1985) Soil cutting and tillage. New York: Elsevier.
Mulqueen, J., J.V. Stafford and D.W. Tanner (1977) Evaluation of penetrometers for measuring soil strength. *Journal of Terramechanics*, **14**(3): 137–151.
Niemi, E.W. and R. Bayer (1970) Analytical prediction of vehicle mobility on muskeg. Technical Report No. 11108, DA-20-018-AMC-0989(T). Warren, Mich.: U.S. Army Tank Automotive Command.
Ohmiya, K. and T. Masui (1988) Visualization software for cone resistance analysis. In *Proceedings of the 2nd Asia-Pacific Conference of ISTVS, Bangkok, Thailand, December*, p. 1–11.
Okello, J.A. (1991) A review of soil strength measurement techniques for prediction of terrain vehicle performance. *Journal of Agricultural Engineering Research*, **50**(2): 129–156.
Olsen, H.J. (1987) Electronic cone penetrometer for field tests. In *Proceedings of the 9th International Conference of ISTVS, Barcelona, Spain*, p. 20–27.
Patin, T.R. (1972) Evaluation of surface shear strength measurements for use in laboratory mobility studies. WES MP M-72-5.
Persson, S. (in preparation) *Advances in Soil Dynamics*. St. Joseph, Mich.: American Society of Agricultural Engineers.
Perumpral, J.V. (1987) Cone penetrometer applications—a review. *Transactions of the ASAE*, **30**(4): 939–944.
Plackett, C.W. (1985) A review of force prediction methods for off-road wheels. *Journal of Agricultural Engineering Research*, **31**: 1–29.
Radforth, N.W. (1952) Suggested classification of muskeg for the engineer. *Engineering Journal*, **35**(11): 1199–1210.
Radforth, N.W. and Burwash, A.L. (1977) Transportation. Chapter 10 in *Muskeg and the Northern Environment*. N.W. Radforth and C.O. Brawner (eds.). Toronto: University of Toronto Press.
Radforth, N.W. and J. Evel (1959) Muskeg impedance factors controlling vehicle mobility. Technical Memorandum No. 57. Ottawa: Canadian National Research Council.
Rawitz, E. and M. Margolin (1991) An economical hand-held recording penetrometer. *Soil and Tillage Research*, **19**: 67–75.
Rohani, B. and G.Y. Baladi (1981) Correlation of mobility cone index with fundamental engineering properties of soil. In *Proceedings of the 7th International Conference of ISTVS*, **3**: 959–990, or WES Miscellaneous Paper SL-81-4, AD-A101409.
Rummukainen, A. (1984) Peatland properties and their evaluation for wood harvesting. Final report for *Harvesting on Peatlands*, a research project of the Nordic Research Council on Forest Operations (NSR), 1977–1983. University of Helsinki Department of Logging and Utilization of Forest Products Research Notes, No. 45.
Saarilahti, M. (1982) Studies on the possibilities of using radar techniques in detecting the trafficability of peatlands. *Acta For. Fenn.*, 176 (in Finnish with English summary).
Saarilahti, M. and M. Tiuri (1981) Radar techniques in detecting the trafficability of frozen peatlands. In *Proceedings of the 7th International Conference of ISTVS, Calgary, Alberta, Canada*, **III**: 1017–1044.

SAE (1967) Off-road vehicle mobility evaluation. SAE Recommended Practice Handbook Supplement, SAE 939. Warrendale, Penn.: Society of Automotive Engineers.

SAE (1985) Passenger car and light truck tire dynamic driving traction in snow. SAE J1466 OCT85. Warrendale, Penn.: Society of Automotive Engineers.

Samset, I. (1975) The accessibility of forest terrain and its influence on forestry conditions in Norway. Reports of the Norwegian Forest Research Institute, No. 32.1.

Scholander, J. (1973) Tear resistance of some forest soils, rupture limit of the field and ground vegetation layer. Swedish Royal College of Forestry, Department of Operational Efficiency, Research Notes No. 61 (in Swedish with English summary, figures, and tables).

Shapiro, L.H., J.B. Johnson, M. Sturm and G.L. Blaisdell (1993) Snow mechanics: Review of the state of knowledge and applications. USA Cold Regions Research and Engineering Laboratory, CRREL Report in progress.

Shoop, S.A. (1989) Thawing soil strength measurements for predicting vehicle performance. *North American Meeting of ISTVS, Victoria, B.C., Canada.* Also USA Cold Regions Research and Engineering Laboratory, CRREL Report 92-17 (1992).

Shoop, S.A. (1992) Precision analysis and recommended test procedures for mobility measurements made with an instrumented vehicle. USA Cold Regions Research and Engineering Laboratory, Special Report 92-7.

Shoop, S.A. and R. Alger (1991) Snow characterization for traction testing: a survey of techniques used. *First Meeting on Winter Mobility, Santa Barbara, California, June.*

Shoop, S.A., B. Young, R. Alger and J. Davis (1993) Comparison of three approaches to traction evaluation on winter surfaces. In *Proceedings of the 11th International Conference of ISTVS, Lake Tahoe, California, September.* Also a CRREL Report in preparation.

Stafford, J.V. and D.W. Tanner (1982) Field measurement of soil shear strength and a new design of field shear meter. In *9th Conference of the International Soil Tillage Research Organization (ISTRO), Yugoslavia.*

Swedish Forest Operations Institute (1992) Terrain classification system for forestry work, developed by Steffan Berg. ISBN 91-7614-078-4. Kolding Lyntryk, Denmark: Skogsarbeten/SkogForsk.

Taylor, H.M., G.M. Roberson and J.S Parker, Jr. (1966) Soil strength-root penetration relations for medium to coarse textured soil materials. *Soil Science*, **102**(1): 18–22.

Thomson, J.G. (1960) Vehicles in muskeg. *Engineering Journal*, **43**(5): 73–78.

Turnage, G.W. and J.L. Smith (1983) Adaptation and condensation of the Army mobility model for cross-country mobility mapping. U.S. Army Waterways Experiment Station Technical Report GL-83-12.

Upadhyaya, S., D. Wulfsohn and J. Mehlschau (1990) An instrumented device to obtain traction related parameters. ASAE Paper No. 90-1097.

U.S. Army (1959) Trafficability of soils. WES TM 3-240 and Suppls., p. 1–15. Vicksburg, Miss.: Waterways Experiment Station.

U.S. Army (1968) Planning and design of roads, airbases, and heliports in the theater of operations, Chapter 9, *Soils Trafficability*, Vol. II of Dept. of the Army Technical Manual TM 5-330 and Air Force Manual AFM 86-3.

U.S. Army (1992) *ALBE Tactical Decision Aid (TDA) User's Guide, Version 2.0.* Misc. Paper GL-92-36.

Voorhees, M.L. and P.N. Walker (1977) Tractionability as a function of soil moisture. *Transactions of the ASAE*, **20**(5): 806–809.

Wasterlund, I. (1990) Soil strength in forestry measured with a new kind of test rig. In *Proceedings of the 10th In-ternational Conference of ISTVS, Kobe, Japan, Aug-ust,* p. 73–82.

Wells, L.G. and O. Tresuwan (1977) The response of various soil strength indices to changing water content. ASAE Paper No. 77-1055, St. Joseph, Mich.: American Society of Agricultural Engineers.

Wong, J.Y. (1989) *Terramechanics and Off-Road Vehicles.* New York: Elsevier.

Wong, J.Y. (1992) Expansion of the terrain input base for nepean tracked vehicle performance model, NTVPM, to accept Swiss rammsonde data from deep snow. *Journal of Terramechanics*, **29**(3): 341–358.

Yong, R.N. and A. Youssef (1978) Application of vane-cone tests on soil for determination of trafficability. In *Proceedings of the 6th International Conference of ISTVS, Vienna, Austria,* **2**: 677–706.

Yong, R.N., A.F. Youssef and E.A. Fattah (1975) Vane-cone measurements for assessment of tractive performance in wheel–soil interaction. In *Proceedings of the 5th International Conference of ISTVS, Detroit, Michigan,* **3**: 769–788.

BIBLIOGRAPHY

Ala-Ilomaki, J. and M. Saarilahti (1990) Rut formation on peat soil—Experiences from a forced-slip wheel tester. In *Proceedings of the 10th International Conference of ISTVS, Kobe, Japan, August,* p. 457.

Baladi, G.Y. (1987) Terrain evaluation for off-road mobility. *Journal of Terramechanics*, **24**(2): 127–140.

Burt, E.C., A.C. Bailey and R.K. Wood (1987) Effects of soil and operational parameters on soil–tire interface stress vectors. *Journal of Terramechanics*, **24**(3): 235–246.

DeRoock, B. and A.W. Cooper (1967) Relationship between propagation velocity of mechanical waves through soil and soil strength. *Transactions of the ASAE*, **10**(4): 471–474.

Dunlap, W.H., G.E. VandenBerg and J.G. Hendrick (1961) Comparison of soil shear values obtained with devices of different geometrical shapes. *Transactions of the ASAE*, **9**(6): 896–900.

Fukue, M., T. Kobayasi and T. Nakamura (1990) Terrain evaluation under water. In *Proceedings of the 10th International Conference of ISTVS, Kobe, Japan, August*, p. 149.

Hendrick, J.G. and A.C. Bailey (1982) Determining components of soil–metal sliding resistance. *Transactions of the ASAE*, **25**(4): 845–849.

Janosi, Z.J. and L.L. Karafiath (1981) Improved technique of field ring shear testing for soil shear strength determination. In *Proceedings of the 7th International Conference of ISTVS, Calgary, Alberta.*

Johnson, C.E., G. Murphy, W.G. Lovely and R.L. Schafer (1972) Identifying soil dynamic parameters for soil–machine systems. *Transactions of the ASAE*, **15**(1): 9–13.

Larson, W.E. and W.R. Gill (1973) Soil physical parameters for designing new tillage systems. In *Proceedings of the National Conservation Tillage Conference, Des Moines, Iowa*, p. 13–22.

Li Guiyou, Li Qin and Li Xiapding (1990) A simple method for measuring the phi value of internal friction angle in saturated paddy soil. In *Proceedings of the 10th International Conference of ISTVS, Kobe, Japan, August*, **I**: 127–134.

Qian Cong, Ren Luquan and Chen Bingcong (1990) Research on reducing adhesion results of soil electro-osmosis and its affecting factors. In *Proceedings of the 10th International Conference of ISTVS, Kobe, Japan, August*, **I**: 45–55.

Reaves, C.A. and R.L. Schafer (1971) Soil measurements related to the performance of soil–machine systems. Presented at the Society of Automotive Engineers Earthmoving Industry Conference, Peoria, Ill., April, Paper No. 710512.

Robbins, D.H. Jr., J.G. Hendrick and C.E. Johnson (1987) Instrumentation for soil–material sliding resistance research. ASAE Paper No. 87-1011. St. Joseph, Mich.: American Society of Agricultural Engineers.

Robbins, D.H. Jr., C.E. Johnson and R.L. Schafer (1987) Modeling soil–metal sliding resistance. ASAE Paper No. 87-1580.

Schafer, R.L., W.R. Gill and C.A. Reaves (1977) Lubricated plows vs. sticky soils. *Agricultural Engineering*, **58**(10): 34–38.

Scholander, J. (1973) Compressive strength of some forest soils. Swedish Royal College of Forestry, Dept. of Operational Efficiency, No. 59 (in Swedish with English summary).

Scholander, J. (1974) Bearing capacity of some forest soils for wheeled vehicles. In *Some Technical Aspects and Consequences*, Swedish Royal College of Forestry, Department of Operational Efficiency, Garpenberg, Sweden, No. 14 (in English).

Smith, L.A. (1978) A recording penetrometer. In *Proceedings of the 4th International Conference on Mechanization of Field Experiments, IAMFE, Iowa State University, Ames, Iowa, July 1976*, p. 336–343, and *Transactions of the ASAE*, **21**(1): 12–14, 19.

Taylor, J.H. (1967) An annular shear device. *Transactions of the ASAE*, **10**(2): 164–165, 169.

Tong, J., Ren Luquan and Chen Bingcong (1990) Reducing adhesion of soil by phosphoric white iron on the basis of bionics principles. In *Proceedings of the 10th International Conference of ISTVS, Kobe, Japan, August*, p. 57–63.

Wilkins, D.E., W.L. Harris and J.H. Taylor (1966) Effect of rate of displacement on shearing stress of soils as measured with a torsional shearing device. ASAE Annual Meeting, Amherst, Mass., June.

Williford, J.R. and L.W. Larson (1968) A study of soil strength values included in cone index readings. ASAE Paper No. 68-666.

Woehrle, W.J. and R.J. Wozniak (1989) Tire traction—matching product and test technologies. SAE Paper No. 890102. Warrendale, Penn.: Society of Automotive Engineering.

Wong, J.Y. (1980) Data processing methodology in the characterization of mechanical properties of terrain. *Journal of Terramechanics*, **17**(1): 13–41.

Wood, R.K. and E.C. Burt (1987) Thrust and motion resistance from soil–tire interface stress measurements. *Transactions of the ASAE*, **30**(5): 1288–1292.

Youssef, A.F.A. (1984) Properties of desert silty soil in relation to vehicle mobility. In *Proceedings of the 8th International Conference of ISTVS, Cambridge, England*, 3: 1217–1233.

Zhang Zhaoxing, Sang Z.Z. and Gao L.R. (1986) Adhesion and friction between soils and solids. *Acta Agromechanica Sinica*, Transactions of the Chinese Society of Agricultural Machinery, **17**(1): 32–40.

Zhenya, S. (1988) Research on the micro-mechanism of soil adhesion. In *Proceedings of the 2nd Asia-Pacific Conference of ISTVS, Bangkok, Thailand, December*, p. 57–63.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1993	

4. TITLE AND SUBTITLE

Terrain Characterization for Trafficability

5. FUNDING NUMBERS

PR: 4A762784AT42
TA: CS
WU: 007

6. AUTHORS

Sally A. Shoop

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

CRREL Report 93-6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of the Chief of Engineers
Washington, D.C. 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Terrain material characterization is needed to predict off-road vehicle performance, trafficability, and deformation (compaction and rutting) resulting from vehicle passage. This type of information is used by agricultural engineers, foresters, military engineers, the auto and tire industry, and anyone else concerned with off-road, unpaved, or winter mobility. This report appraises the state-of-the-art of terrain (or substrate) characterization techniques for vehicle traction studies. It concentrates on field measurement of strength-related properties for soil, snow, muskeg, and vegetation, but also discusses how these compare with laboratory measurements and the importance of other terrain features (slopes, drainage, and obstacles).

14. SUBJECT TERMS

Mobility, Soil, Traction, Vehicle, Muskeg, Strength, Trafficability, Snow, Terrain, Vegetation

15. NUMBER OF PAGES 30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102