Special Report 89-31

September 1989

**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Vehicle mobility on thawing soils

Interim report on CRREL's test program

Sally A. Shoop

AD-A215 148

DTIC
ELECTE
DEC 07 1989
S E D

89 12 06 089

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188
Exp. Date· Jun 30. 1986

1a. REPORT SECURITY CLASSIFICATION	1B. RESTRICTIVE MARKINGS
Unclassified	

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
Special Report 89-31	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION
U.S. Army Cold Regions Research and Engineering Laboratory	CECRL	Office of the Chief of Engineers

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
72 Lyme Road Hanover, N.H. 03755-1290	Washington, D.C. 20314

8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
	6.27.30A	4A762730 AT42	A	005

11. TITLE (Include Security Classification)

Vehicle Mobility on Thawing Soils: Interim Report on CRREL's Test Program

12. PERSONAL AUTHOR(S)
Shoop, Sally A.

13a. TYPE OF REPORT	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) September 1989	15. PAGE COUNT 21

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Frost Effects Research Facility, Road damage
			Laboratory tests, Thawing soils
			Mobility testing Vehicle mobility. (TXJ)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Although vehicle mobility in soft and wet soil has been studied in the past, the more complex problem of vehicle mobility on thawing soils has not been addressed. This problem is being examined in CRREL's Frost Effects Research Facility (FERF), where field-scale testing can be conducted under controlled conditions. The soil is frozen and then thawed to the desired test conditions. Traction and motion resistance are measured using an instrumented vehicle. To date, mobility testing has been conducted for nine different thawing conditions of a frost-susceptible silt. The failure mechanisms of the tire–soil interaction were observed, the soil strength was calculated, and vehicle performance was analyzed. For the tire and soil conditions tested, the initial failure of the tire–soil interaction is totally within the soil. At higher tire slip the failure occurs at or near the tire–soil interface. The shear strength data calculated from the vehicle test results indicate that the soil is basically frictional in behavior, with little or no cohesion, however, there is apparent cohesion from soil tension at low moisture contents. Of the soil parameters measured, vehicle traction is most strongly influenced by the soil friction. In turn, soil friction and cohesion are influenced by moisture content, density and thaw depth.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
[X] UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
Sally A. Shoop	603-646-4100	CECRL-EA

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

PREFACE

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

ii

CONTENTS

ILLUSTRATIONS

TABLES

Vehicle Mobility on Thawing Soils
Interim Report on CRREL's Test Program

SALLY A. SHOOP

INTRODUCTION

In the past, the vehicle mobility research at CRREL has concentrated on mobility on snow and ice. However, during warming trends, the unique combination of thawed wet soil over frozen impermeable ground causes many problems for vehicle mobility. Thawing ground is a common problem for vehicle traffic both in Europe and North America, as well as many other places affected by seasonal or perennial frost. Roads are often closed or restricted and the traffic that does pass may cause significant damage to both paved and unpaved surfaces. The subject of vehicle mobility on thawing soils has not been studied in the past, primarily because of the complex nature of the problem, the scattered and relatively short occurrence of the thaw, and the difficult working conditions it presents. Although intermittent and springtime thaws can be relatively short lived, they remain a critical and unsolved problem for vehicle mobility and road management.

The unique capabilities of CRREL's Frost Effects Research Facility (FERF) allow us to create carefully controlled thawing ground conditions on a large scale. With this facility, the mobility of full-scale vehicles on thawing soil can be tested throughout the year regardless of the outside temperature. An experimental program to evaluate the effect of thawing soil conditions on vehicle performance has begun. Full-scale mobility tests are performed using the CRREL Instrumented Vehicle (CIV) to measure traction and motion resistance. In addition to the experimental program in the FERF, mobility on thawing soils is studied analytically using the principles of soil mechanics and traction mechanics, and numerical modeling techniques. The analysis concentrates on defining the mechanics of vehicle traction on thawing ground, the failure mechanism controlling the tire–soil interaction and the interaction of the frozen and thawed soil layers. Our ultimate goal is to develop a scheme that will allow us to predict vehicle mobility on thawing ground.

This paper is a preliminary report intended to describe the test facilities, test method and the results to date. A literature review is also included that presents the state of the art. Since this is a long-term project, results are preliminary and serve to guide future efforts.

LITERATURE

Vehicle mobility on thawing soils

Thawing ground presents severe difficulties for vehicle mobility, yet scientific study of the problem has not been attempted. Knowledge of the subject has remained at a rudimentary level because of the complicated and elusive nature of thawing ground and because of the difficulty it presents for vehicle traffic. However, several studies have been done that relate indirectly to different aspects of the problem.

The work most closely addressing mobility on thawing ground is studies of the environmental effects of travel on thawed ground. This type of study was very popular in the 1970s during the oil boom and the building of the pipeline in Alaska. CRREL and the Muskeg Research Institute in Canada were heavily involved in this effort and studied both the short- and long-term effects of off-road traffic on tundra (for example, Burt 1971, Radforth 1972, Radforth and Burwash 1973, Rickard and Brown 1974, Abele et al. 1984). Wheeled, tracked and hovercraft vehicles were studied, but the emphasis was on the environmental impact rather than vehicle performance. In the process, however, the vehicle parameters, ground type, moisture content, rut depth, etc., were recorded and these give some indication of vehicle performance.

Another area related to traffic on thawing soils is tne work done in the transportation community regarding road and highway shut-down dates and load restrictions to prevent damage during the spring thaw (Wiman 1982, Rutherford et al. 1985, Allen and Bullock 1987). Most of these studies look at the effect of spring thaw on the strength of a pavement system. The failure of the pavement in spring is primarily attributable to thaw weakening of the subbase or subgrade soils.

Vehicle mobility on layered soils

Off-road mobility research on layered soils is particularly applicable to the thawing soils problem. Swanson and Patin (1975) conducted small-scale tests in layered soils and found that mobility problems occur when the layers become thin. A thin, strong layer over a weaker layer causes the tire performance to decrease slightly as the strong layer becomes thinner, and to decline rapidly when the strong layer is thin enough so that the tire breaks through. This behavior strongly affects vehicle motion resistance and is similar to the behavior of pavements.

By an entirely different mechanism, a thin, soft layer over a hard layer can significantly reduce a tire's tractive performance. The firm lower layer prevents sinking and, therefore, influences motion resistance, while the thin upper layer more strongly influences traction. The top, soft layer acts as a lubricant over the firm layer, and even after several passes the tire does not fully penetrate the thin layer of soft soil. This is quite similar to the thawing soils case.

Theoretical formulation of what happens to a tire on a multilayered soil was presented by Karafiath (1975), who did his work under contract to the U.S. Army Tank Automotive Command (TACOM). In his model, the tire–soil interaction is treated as a modification of the bearing capacity problem, which is solved by applying the plasticity theory of velocity fields. He varied the strength of the soils with depth, concentrating on the two-layer case. His numerical simulation compared acceptably with experiments at the U.S. Army Engineer Waterways Experiment Station (Swanson and Patin 1975). Karafiath emphasized, however, that the model was limited by the validity of the input. In particular, the stresses at the layer interface are unknown and existing field techniques to measure the strength of each of the soil layers are unsuitable.

Strength of thawing soils

It is apparent that soils lose their strength during initial thawing because of increased moisture con-

tent, particularly since the melting ice is initially unbound to the soil particles. During freezing, the soil moisture often increases due to moisture migration to the freezing front. Upon thawing, the additional moisture cannot readily drain because of the impermeable frozen layer beneath the thawed zone. The frozen layer also prevents the water added from snowmelt and rain from draining. With time and continued thaw, however, the additional moisture drains or evaporates, and the soil strength may increase, in some cases, to values even higher than those in the equivalent unfrozen ground because of particle reorientation (Alkire and Jashimuddin 1984).

The strength of thawing soil has been studied by several researchers. Much of this effort has been aimed at examining the weakening of a pavement subsurface during thaw, specifically, the effect of freeze–thaw cycles on the resilient modulus of the soil. In the field, the thaw weakening of pavement sections is measured with a falling weight deflectometer. Laboratory and field measurements of the strength of a silt subgrade after freezing and thawing cycles was reported by Johnson et al. (1978). They found that moisture content had the most significant effect on the resilient modulus, with deviator stress having a lesser effect. The resilient modulus ranged from 10^4 MPa for the frozen silt to less than 4 MPa for the thawed silt.

While the pavements work is concerned with bearing strength, which influences the motion resistance of a vehicle, vehicle traction is also strongly influenced by the shear strength of the soil and the interaction at the soil–tire interface. Zhiquan (1983) carried out laboratory shear tests on thawing soil and found that the weakest zone in thawing was not necessarily at the freeze–thaw interface but rather at the zone of the highest moisture content. Mikhailov and Bredyuk (1966) report that the shear strength of the thawed soils tested was 10 to 40% lower than that for the same unfrozen soils at identical moisture. Nixon and Hanna (1979) found that the shear strength of thawed permafrost soils (mostly silts) tended toward zero at water contents of 35 to 42%.

Chamberlain et al. (1988) and Blaisdell et al. (1987) have looked at the strength of frozen and thawed soils specifically for off-road mobility predictions. Soil cores were tested in the laboratory in triaxial compression at a range of temperatures. They found that the two most important factors influencing the strength of the frozen soil are the degree of saturation and temperature, while for thawed soils, strength was also dependent on dry density and strain rate. They also noted that for

strain rates higher than 10% per second, the effects of strain rate are small compared to effects of moisture and density. The strength of the fine-grained samples was an order of magnitude lower when thawed than when frozen.

EXPERIMENTAL METHOD

Because of the large number of variables affecting vehicle mobility in thawing soils and the time required to generate a given set of experimental conditions, our initial mobility experiments concentrate on evaluating what are anticipated to be the most critical variables. From studies of traction mechanics and from the literature, the most important soil parameters are probably soil type, thaw depth, soil moisture content and soil density in the thawed zone. Thus, the experimental program is designed around testing a wide range of soil types, thaw depths, moisture contents and densities. A large-scale test basin was constructed to create the desired soil conditions, and vehicle traction and motion resistance were tested using a full-scale instrumented vehicle.

Experimental design

The factors that influence vehicle mobility in thawing soils can be roughly grouped into those that pertain to the soil conditions and those that characterize the vehicle. Because of the time involved in doing each test, only a limited number of factors can be varied. Therefore, the parameters that are currently considered to be the most critical were varied. Meanwhile, other parameters are fully documented for later analysis. For the initial test program, we decided that most of the vehicle parameters will remain constant, with only the tire pressure, the number of passes over the soil and the normal load on the tires being change... The experiments are designed primarily to evalu. te the effect of various soil conditions.

The soil conditions expected to be ci. cal to vehicle mobility on thawing soil, as mentioned before, are soil type, moisture content, density and depth of thaw. These parameters are also relatively easy to measure in the field and, therefore, are reasonable as input to a mobility model. Three types of soils will be tested over the life of the project. The first soil to be tested is a sandy silt that is highly frost-susceptible. The experimental program, as described below, will be repeated (and modified as necessary) for each test soil type.

Since there are three primary soil variables that we expect to have the greatest influence on mobility, the program design is similar to a three-factor-
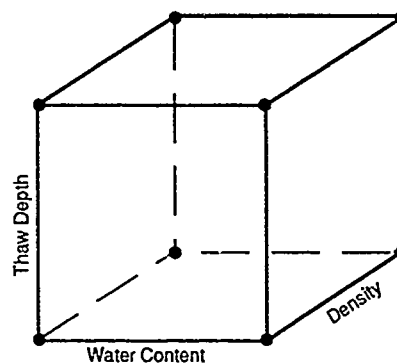

Figure 1. Three-factorial experimental design concept used to evaluate the soil variables influencing vehicle mobility on thawing ground.

ial experiment, as shown in Figure 1. This is not a true factorial design, however, since the variables cannot be precisely controlled and the conditions represented by the corners of the cube cannot be created exactly. Moisture content, for example, is obtained indirectly by varying freeze rate, the depth to the water table, and how much water (if any) is added by rain and snow melt. The idea, however, is to vary the design factors to test a wide variety of conditions, represented by the corners of the cube. In this way, we can use a response surface analysis and the effect of the test variables should become clear. The results will indicate the effects of thaw depth, moisture content and density on traction and motion resistance.

Each set of soil conditions is tested at two or more tire inflation pressures. This will not only quantify the effect of tire contact pressure on mobility, but the data obtained are also used to characterize the soil strength, as discussed later. The effects of multiple vehicle passes and changing the normal load on the wheels are also measured.

Each traction and motion resistance test is repeated a minimum of three times. Additional tests are run depending on available untracked soil. Parameter effects that are of the same order of magnitude as the experimental error (experimental error for traction is a tractive coefficient of 0.03), can be detected with a confidence level of 99% after completion of the test series. Future experiments will depend on the results from the first set of data. As time allows, other factors can be added to the design and additional experiments can be run to refine the results.

Test basin

The experimental work takes place in the Frost Effects Research Facility (FERF). The unique capa-
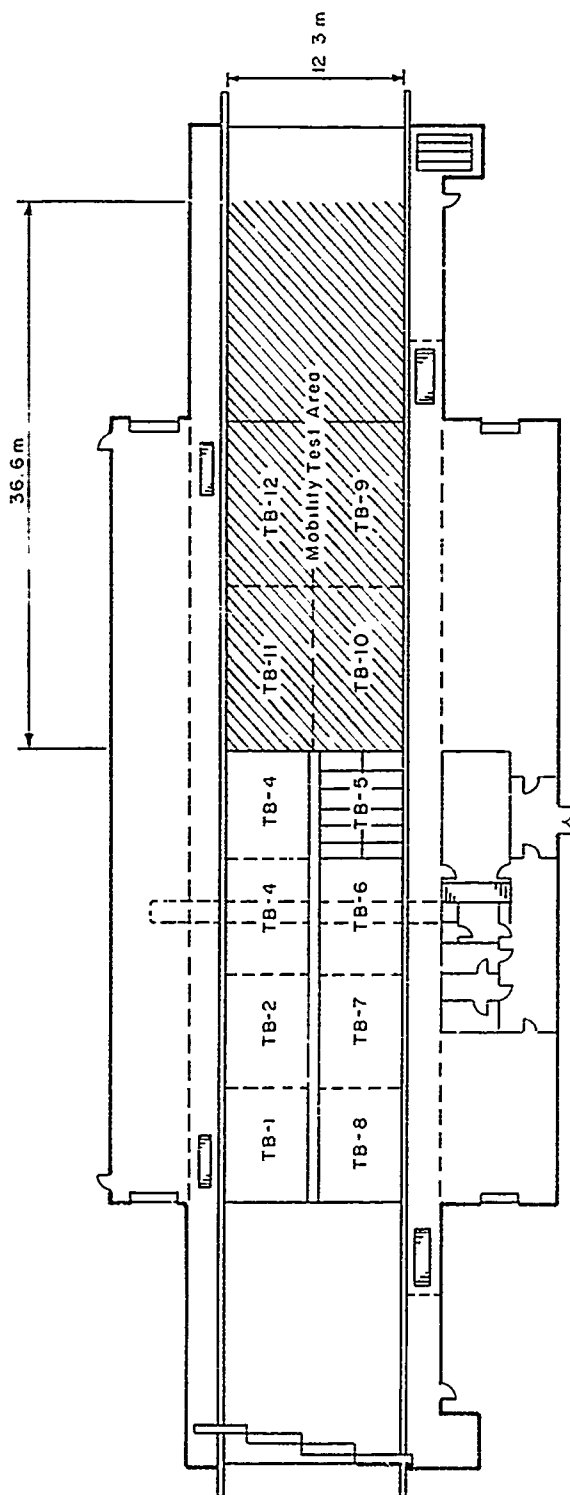
Figure 2. Plan view of mobility test basin in the Frost Effects Research Facility.
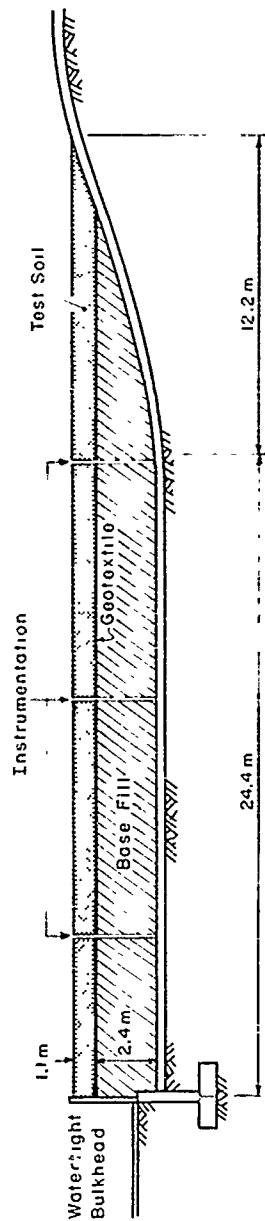

Figure 3. Cross section of the mobility test basin.

4

bilities of the FERF allow experimental conditions, including freezing and thawing rate and depth, water table, soil moisture content and density, etc., to be carefully controlled. The soil can also be reconstituted to repeat test conditions and to maintain soil conditions throughout the experimental program.

The mobility test basin in the FERF is 36.6 m long and 12.3 m across (Fig. 2). The test area is split in half along its length, and testing takes place on one half while the other half is being frozen. The basin consists of a base layer of fill and a layer of test soil separated by a geotextile (Fig. 3). We chose the soils based on their compaction characteristics, bearing capacity, frost-susceptibility and cost. The purpose of the base soil is mainly as a fill material to simulate a natural environment; it is also used to add and fluctuate the water table. The base soil is a bank run sand from Pompy Pit, East Thetford, Vermont. The test soil is a silt from Lebanon, New Hampshire, which is highly frost-susceptible yet easy to work with (easily drained, tilled and compacted). This soil is marginal to unacceptable for use on local roads, so it is a good example of off-road or back-road conditions. The grain size distribution of the Lebanon silt is shown in Figure 4. Additional information for both of the soils, such as hydraulic conductivity, moisture retention and compaction curves, etc., can be found in Shoop (1988). The performance of the geotextile as a capillary break during freezing and thawing will also be monitored.

Instrumentation

Temperature and soil moisture are monitored with thermistors and tensiometers respectively. We chose thermistors over thermocouples because of their accuracy and reliability. Tensiometers are used in conjunction with a "soil moisture retention curve" to determine soil moisture and to monitor the water table and moisture migration as the soil freezes and thaws.

The bulk of the soil instrumentation is concentrated in the upper 30 cm because this is the area that most strongly influences the mobility of the test vehicle (a Jeep Cherokee). The shallow sensors are removed following testing and replaced after the soil is tilled and recompacted in preparation for the next freezing cycle. The instrumentation below the 30-cm level is spaced every 15 cm or more and is installed permanently. The thermistors were assembled on polyethylene rods and inserted into the soil through a borehole. The tensiometers were placed in the soil as the test cell was built. Figure 5 shows the configuration of the instrumentation.

Testing procedures

To prepare the soil for testing, it is first tilled and then compacted to the desired density at a specified water content. The soil is frozen from the surface downward using refrigeration panels, and when the required frost depth is obtained, the panels are removed. In the first two freeze cycles, the soil is frozen to a depth of 1.2 m or more to condition it. For the remaining freeze cycles, the soil is frozen to
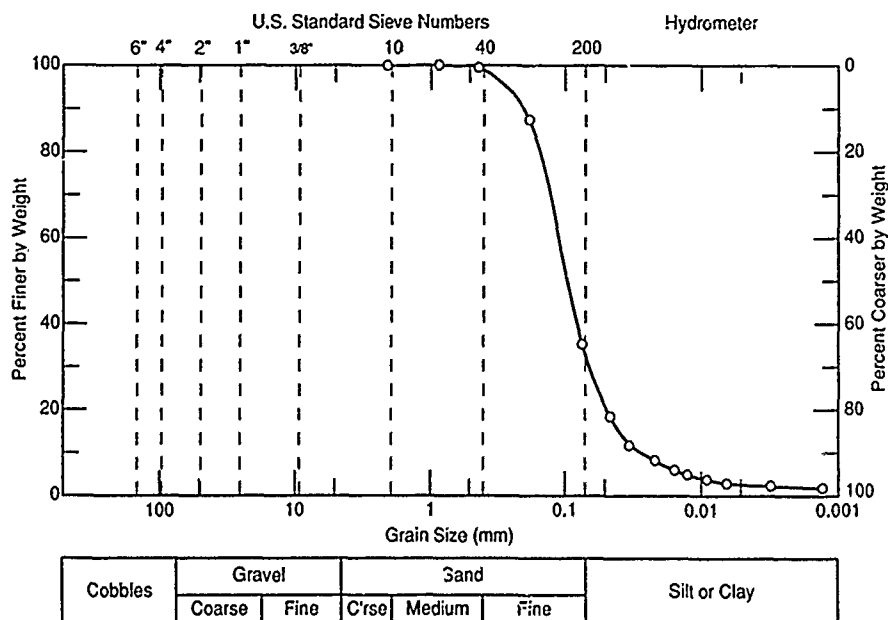

Figure 4. Grain size distribution curve for the Lebanon silt test soil.
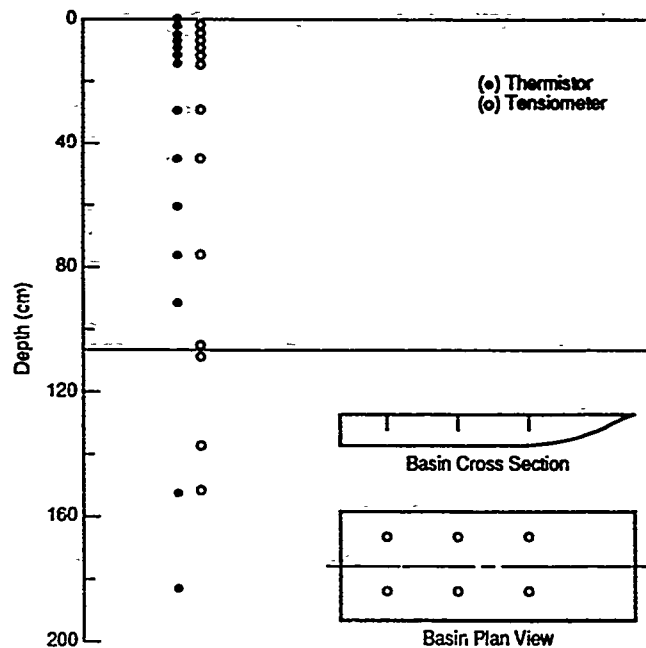
5

Figure 5. Instrumentation locations in the mobility test basin.

a depth of 46 to 60 cm. While the soil is still frozen, cores are taken to determine ice lense growth and also to measure soil strength in the laboratory. The frozen soil surface is generally surveyed to determine the amount of frost heaving. The soil is then allowed to thaw by maintaining "spring-like" air temperatures within the building (7 to 13°C).

When the soil has thawed to the desired depth, it is tested for moisture content, density and strength. Soil samples are obtained using a drive cylinder, and density and moisture content are determined in the conventional method by oven drying the samples. Depending on soil conditions, moisture content and density are also measured by use of a nuclear probe. Cone penetrometer readings are used to assess the degree of homogeneity over the test basin and as a strength index.

The mobility testing is conducted with the CIV, described by Blaisdell (1983), using both traction and rolling resistance tests. Figure 6 shows mobility testing in the FERF. The CIV is instrumented to measure the forces at the front wheels in three perpendicular directions. It also measures the speed of each of the front wheels and the true vehicle speed. Additional measurements and instrumentation are added as desired.

To measure traction, a braking force is applied to the rear wheels of the CIV, while the front wheels are driven. The operator keeps a constant vehicle speed as measured by a fifth wheel. (All tests in this study were done near 4.8 km/hr.) The wheel speed is gradually increased while the operator holds the vehicle speed constant by applying the rear brakes. The resulting slip of the front wheels is recorded as the wheel to ground Differential Interface Velocity (DIV), which is the speed of the wheel minus the true vehicle speed. The traction is generally reported as the tractive coefficient: longitudinal force divided by vertical force.

Motion resistance is measured by the longitudinal force on the front wheels while the vehicle is driven with rear wheels. Again, the vehicle is operated at a constant speed. The motion resistance in the soil is measured with reference to the motion resistance on a hard surface, deter-

Figure 6. Mobility testing on thawing soils in the Frost Effects Research Facility.

6

.mined using the same tire type and inflation pressure. The hard surface motion resistance is measured on an asphalt road near the FERF.

After testing, the soil is thoroughly thawed. It is then tilled and recompacted and, in this way, experiments can be repeated with the same soil conditions.

CONDITIONS TESTED

Nine different soil conditions have been tested to date. For most cases, the soil was tested at two different thaw depths for each freeze cycle. Therefore, for tests on consecutive days, the difference in soil density and moisture is solely because of the continued thaw. Table 1 lists the thawed soil conditions for each test. The average depth of thaw was taken as a combination of the depth of the 0°C isotherm as read on the thermistors and the average of several physical measurements of thaw depth made by digging down to the frozen layer. For the most part, these two measurements agreed. However, the thaw depth could vary up to ± 2.5 cm within the test section because of the roughness of the initial soil surface, air currents in the building, etc. Cone penetration was also measured for each set of test conditions and is shown in Table 1 as both Cone Index (CI) and Cone Gradient (CG). The CI and CG are calculated only for the zone of thawed soil because the cone could not penetrate the frozen layer.

The soil conditions listed in Table 1 represent only part of the experimental program, since testing on this soil is not yet complete. The distribution of conditions tested so far are dryer and stronger than originally anticipated and are compared to the goal of the entire test program in Figure 7. Conditions tested include a wide range of thaw depths and dry to wet moisture conditions. However, the saturated and supersaturated conditions, which
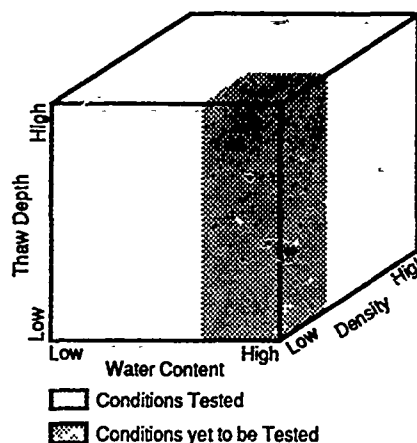

Figure 7. Soil conditions tested to date.

are often the worst for vehicle mobility, have not yet been tested. These conditions are more difficult to create in the test basin. A high water table was recently added to generate the frost heave needed for saturated and supersaturated soil conditions.

The soil conditions before freezing were also recorded as part of a validation study for numerical models of frost heave. A frost heave prediction model can be used to predict the thawed soil conditions and, therefore, it can be used to determine the initial soil conditions, freeze rate and other experimental controls needed to obtain the desired thawed conditions.

Two different tires were used in the course of this study. The first set of tests (on 16 and 17 March) used tire D. These tests were preliminary and were intended as trials for developing the test technique. Because of these inconsistencies with the remainder of the test program, much of the data from the trial tests are not included in the analysis. Tire A was used for the rest of the test program. The characteristics of both tires are listed in Table 2.

Table 1. Soil conditions tested.

Test date (1988)	Dry density (g/cm³)	Moisture content (%)	Saturation (%)	Thaw depth (cm)	Cone index	Cone gradient
16 Mar	—	8.0	—	8.3	285	132
17 Mar	—	9.7	—	15.2	283	54
4 May	1.48	9.7	32.5	5.7	270	158
5 May	1.50	6.8	23.5	11.4	236	82
18 May	1.51	11.8	41.4	8.9	206	102
9 Jun	1.58	21.0	82.0	10.2	258	81
10 Jun	1.65	17.5	77.4	14.0	182	60
19 Jul	1.48	24.8	82.8	2.5	254	255
20 Jul	1.63	17.7	75.5	6.4	89	65

Table 2. Tire characteristics.

Inflation pressure (kPa)	Contact area (cm²)	Tread width (cm)	Deflection (%)	Section height (cm)	Section width (cm)	Tire dia. (cm)
			Tire D			
179	279.3	13.7	—	17.1	21.6	72.4
103	345.1		28			
			Tire A			
179	354.1	15.7	28	16.4	22.9	73.7
103	487.6		38			

Table 3. Average motion resistance coefficient and peak (net) tractive coefficient. Each entry is the average of two to five tests.

Test date (1988)	Motion resistance coefficient $\times 10^{-3}$				Peak tractive coefficient			
	179-kPa pressure		103-kPa pressure		179-kPa pressure		103-kPa pressure	
	Left	Right	Left	Right	Left	Right	Left	Right
16 Mar	−0.9	6.9	44.9	41.8	0.516	0.485	0.621	0.573
			[32.3]	[34.5]*				
17 Mar	25.8	9.4	28.4	16.9	0.472	0.525	0.562	0.579
4 May	13.5	9.4	29.1	32.1	0.578	0.582	0.612	0.633
5 May	11.6	21.4	29.7	37.8	0.520	0.514	0.550	0.552
18 May	26.9	23.5	33.6	21.7	0.493	0.506	0.578	0.582
9 Jun	25.0	16.4	36.4	33.4	0.595	0.621	0.640	0.627
	[7.1]	[4.0]*	[3.3]	[3.6]				
10 Jun	25.3	28.4	34.6	39.9	0.614	0.599	0.657	0.585
	[9.2]	[13.9]	[26.7]	[30.5]				
19 Jul	19.6	13.3	36.2	25.1	0.620	0.647	0.604	0.662
			[26.1]	[19.5]				
20 Jul	27.2	25.0	33.4	30.0	0.596	0.651	0.595	0.619
	[12.2]	[11.0]	[23.8]	[20.0]				

* Numbers in brackets are motion resistance values obtained from a hard surface.

ANALYSIS

The peak traction and average motion resistance values for the conditions tested are listed in Table 3. The forces measured with the CIV load cells during a traction test are net traction values. The tractive coefficients reported are for the peak net traction and are obtained from a point-by-point division of the longitudinal force and the vertical force.

Motion resistance values obtained using the CIV are the average of the longitudinal forces on the front wheels. Motion resistance is divided by the normal force on the wheel to give the motion resistance coefficient reported in Table 3. For this calculation an overall average normal force of 6174 N was used. No trends can be distinguished from the motion resistance values. The reason for this is that either the test variables did not affect motion resistance or that the standard testing procedure was not sensitive enough to detect the effects. The motion resistance measured on a hard surface was also recorded and is shown in Table 3. Later in the test program, the hard surface measurement was routinely done as part of the test sequence. The hard surface values are subtracted from the resistance values, leaving only the effect of the terrain. These "corrected" resistance values will be used for analysis when more data are collected.

The test results obtained so far have been analyzed to determine the failure mechanisms caused by the tire–soil interaction and the relationship between soil parameters and vehicle performance. The mechanism of shear failure at the tire–soil interface was visually observed and recorded. The tractive coefficient curves were compared to the traction curves from other types of soils, as well as those for snow and ice, to determine shape and other unique characteristics. Peak traction and motion resistance were correlated with the measured soil parameters and the calculated soil strength to determine influence of soil properties on vehicle performance.

Failure mechanisms

To mathematically analyze the traction and slippage, it is important to understand the physical mechanisms involved within the tire–soil interaction. For this reason, the mode of failure as the tire slipped was carefully observed. In short, the failure mode progressed from a bearing capacity type failure of the soil at low DIV to a tire–soil interfacial shear at high DIV. This progression was particularly obvious in the dryer soil conditions.

Within the yield zone of the bearing-capacity type failure, the soil can be described as failing in general shear or plastically. For most cases tested, at low DIV the plastic zone culminates in a rupture surface within the soil at a depth of approximately 5 to 8 cm. As the torque on the wheel increases, the shear stress applied to the soil increases and the geometry of the yield zone changes as shown in Figure 8. The higher shear stress applied at the
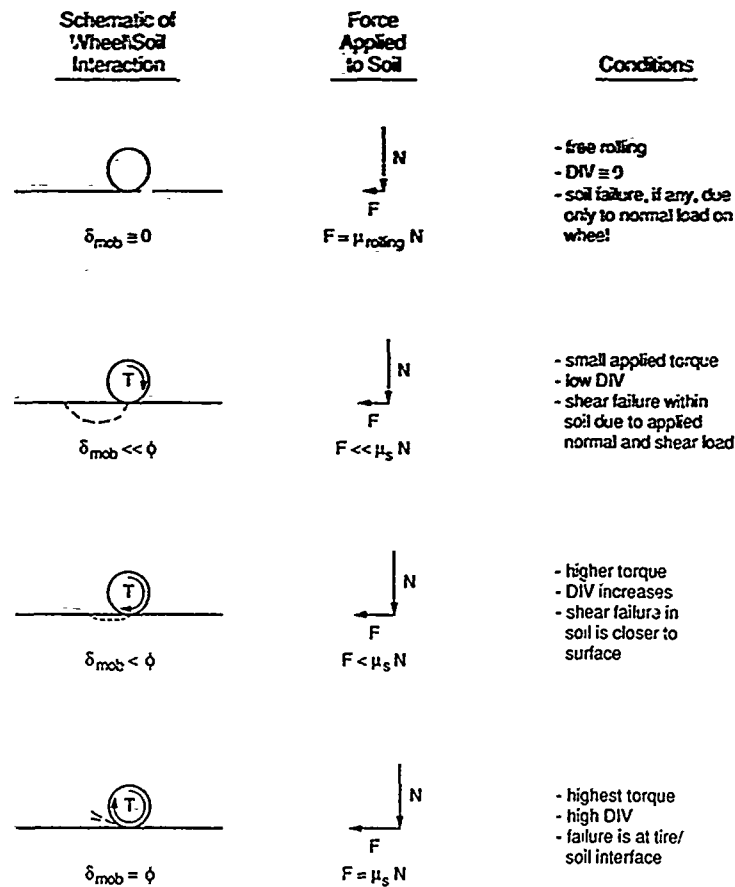
8

Schematic of Wheel/Soil Interaction	Force Applied to Soil	Conditions
$\delta_{mob} \cong 0$	N F $F = \mu_{rolling} N$	- free rolling - DIV ≅ 0 - soil failure, if any, due only to normal load on wheel
$\delta_{mob} \ll \phi$	N F $F \ll \mu_s N$	- small applied torque - low DIV - shear failure within soil due to applied normal and shear load
$\delta_{mob} < \phi$	N F $F < \mu_s N$	- higher torque - DIV increases - shear failure in soil is closer to surface
$\delta_{mob} = \phi$	N F $F = \mu_s N$	- highest torque - high DIV - failure is at tire/ soil interface

Figure 8. Relationship among forces applied to wheel, forces applied to soil surface and the nature of soil failure behind the tire. (T = torque on wheel; N = normal force applied to soil; F = shear force applied to soil; $\mu_{rolling}$ = coefficient of rolling friction; μ_s = coefficient of sliding (or slipping) friction = tan δ; φ = soil internal angle of friction; δ = interface angle of friction between tire and soil; δ_{mob} = "mobilized" interface friction angle; DIV = Differential Interface Velocity).

tire–soil interface causes the plastic failure zone to be more shallow. At this point the tire breaks away and begins to dig down into the soil as the tire lugs move the soil at the interface away. This sequence of behavior was observed in many of the traction tests.

This concept is supported by numerical analysis done by Karafiath and Nowatzki (1978). Figure 9 shows slip line fields, denoting zones of plastic failure, that were calculated for a pneumatic tire on soil for increasing values of mobilized tire–soil interface shear angle δ_{mob}. An increase in δ_{mob} can be generated by increasing the torque on the wheel; therefore, this sequence of figures is analogous to the yield zone developed as torque on the wheel increases (such as is generated in a typical traction test). At low torque, a small percentage of the

interface friction is developed. The plastic failure zone in the soil is larger and deeper as shown in the top figure where $\delta_{mob} = 5°$. As the torque increases, the shear stress applied to the soil surface increases and δ_{mob} increases to a maximum value. This causes the failed zone to be at or near the soil–tire interface (bottom figure) and the wheel begins to dig into the soil.

The changes in the stress state with increasing torque are very important for layered or thawing soils where the underlying layer is much stronger than the overlying soil. The stresses dictate how the tire and soil will interact and, therefore, the traction of the vehicle. When the frozen soil layer is within 8 cm of the surface, the yield zone may intersect the frozen layer and the nature of the soil failure is affected. For these cases, the plastic zone culmi-
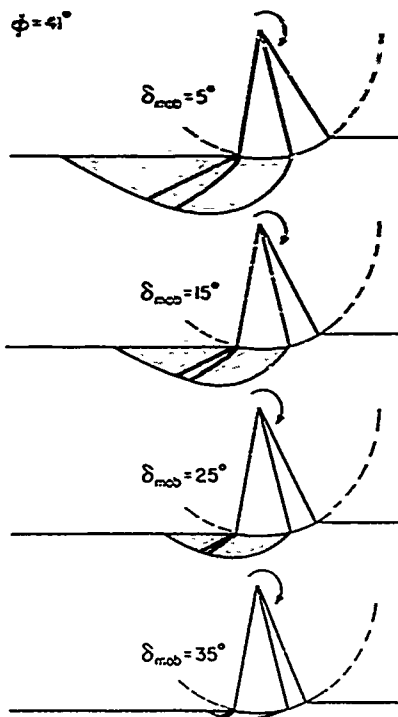
$\phi = 41°$

$\delta_{mob} = 5°$

$\delta_{mob} = 15°$

$\delta_{mob} = 25°$

$\delta_{mob} = 35°$

Figure 9. Geometry of the rear slip line fields for increasing values of δ_{mob} (after Karafiath and Nowatzki 1978).

nates at the interface between the thawed and frozen ground. This is not because the interface is a zone of weakness but because the thawed layer is in a failed, plastic state and the stronger, frozen layer is not. When the yield zone intersects the frozen layer, the tractive coefficient is greater. The experimental traction data suggest that for similar moisture conditions, the tractive coefficient is greater when the frozen layer is shallow.
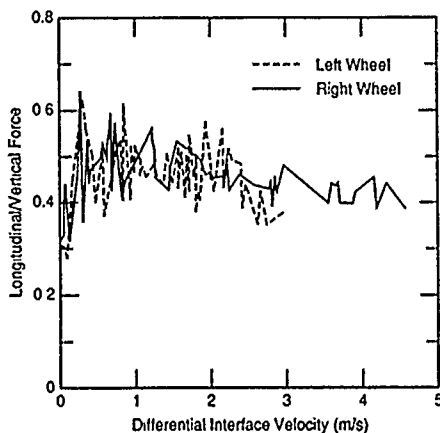
Traction curves

Traction curves indicate the nature of the soil–vehicle interaction in terms of the development of the traction of the vehicle and the failure of the soil or soil–tire interface. The traction curves are plotted as tractive coefficient (longitudinal force divided by vertical force) vs DIV (the difference between the velocity of the wheel and the velocity of the vehicle). The calculations and curves are computed for each wheel separately. Figures 10 and 11 are examples of the raw data obtained with the CIV. Obviously, these curves have not been smoothed.

The traction curves for thawing silt have a unique blend of characteristics. The material tested generally holds a constant or near constant traction coefficient for a wide range of DIV. Unlike snow, where a significant amount of traction is lost at increasing DIV, or ice, where traction is lost very quickly at small DIV, the traction on the thawing silt tested tends to drop only slightly (Fig. 10) or remain constant (Fig. 11) for increasing DIV.

Generally, the peak type curves (Fig. 10) indicate cohesive soils, while the asymptotic type curves (Fig. 11) represent noncohesive soils. The tractive coefficient obtains its maximum value between 0.3 and 1.2 m/s DIV, usually between 0.3 and 0.6 m/s. At higher DIV, the traction either remains at peak level or decreases slightly to a residual value. For thawing soils with low moisture content, a pronounced peak or hump in the traction curve is common (Fig. 10). The soil behaves cohesively at low moisture content because of the high soil tension in the pores. Once this tension is destroyed, the shear strength of the soil decreases, and thus, traction decreases. The traction curves tend to be asymptotic at higher moisture content, particularly at the
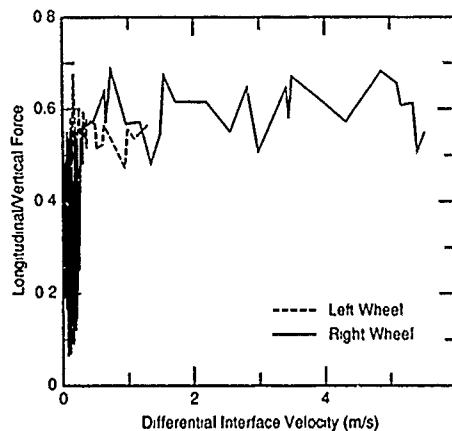

Figure 10. A peaked traction curve is common when the moisture content of the silt is low (raw data).

Figure 11. Asymptotic traction curve is common for shallow thaw depths (raw data).

10

higher contact pressure (when tire inflation pressure is 179 kPa).

When the thickness of the thawed soil is small, the traction coefficient does not drop as the DIV increases, i.e., the curve is asymptotic. This is partly because of the additional support and strength provided by the shallow frozen soil layer. At low DIV, the soil yield zone abuts the frozen layer and traction coefficients are high. At increased DIV, where the failure or slip is at the tire–soil interface, the tire quickly excavates the soft thawed layer, digging down to the frozen layer. The frozen layer provides higher traction than the thawed soil and the traction coefficient remains high.

When the frozen layer has a high frozen water content, the heat of friction at the tire–soil interface may melt the ice at the surface of the frozen layer and cause a loss of traction by lubricating the interface. This effect has not yet been observed because the ice content in the frozen soil has been low. A water table has been added to the test basin that will increase the amount of water drawn to the freezing front and, consequently, increase the ice content in the frozen layer, and this effect may be observed in future tests.

Soil strength

Several methods to determine in-situ soil strength exist. None of these are entirely satisfactory for predicting the failure of the soil as it affects vehicle mobility. This is also true of the cone penetration measurements we recorded. Therefore, this study also includes in-situ soil strength as measured directly by the vehicle for comparison with other techniques. The measurement technique and results are discussed here. Based on the promising results reported in this paper, a more thorough study is planned.

The soil strength parameters characterizing the failure caused by the normal and shear load of a pneumatic tire slipping on the soil surface were calculated from the vehicle traction data. Traction tests were conducted at two tire inflation pressures (therefore, two contact pressures) so that soil strength parameters, c (cohesion) and ϕ (internal angle of friction), could be calculated based on the Mohr–Coulomb failure criteria. Because the traction is an interaction between the vehicle and the soil, c and ϕ are not necessarily the same as the parameters c and ϕ used in soil mechanics. More important is that the stress conditions and failure mechanisms of a pneumatic tire on soil are exactly duplicated and, therefore, c and ϕ measured in this way should be representative of the strength parameters needed for mobility calculations and predic-

tions. The traditional soil strength parameters are also measured in the laboratory and with a shear annulus device; a more thorough treatment of this subject will be presented at a later date. In any case, the c and ϕ values were calculated from peak gross traction values, which occur at low DIV, and were observed to coincide with a failure of the soil and not with failure at the soil–tire interface. Therefore, these values should be similar to the shear strength characteristics of the soil (assuming a similar stress state).

The method of calculating c and ϕ is based on the Mohr–Coulomb failure criterion

$$\tau = c + \sigma_n \tan \phi \qquad (1)$$

where τ = shear stress at failure
c = cohesion
ϕ = internal angle of friction
σ_n = normal stress at failure.

Multiplying eq 1 by the contact area of the tire and rewriting in terms of forces yields

$$T = cA + N \tan \phi \qquad (2)$$

where T = shear force acting at the soil–tire interface or gross tractive force (net traction plus motion resistance)
A = tire contact area
N = normal force on wheel.

The tire contact area A can be varied by changing the inflation pressure. For two inflation pressures, 103 and 179 kPa, eq 2 can be written

$$T_{103} = c A_{103} + N \tan \phi$$
$$\qquad (3)$$
$$T_{179} = c A_{179} + N \tan \phi.$$

Since T, A and N can be measured, c and ϕ can be calculated by simultaneously solving the two equations. Thus, the strength parameters, c and ϕ, are obtained.

By use of this method, c and ϕ were calculated for each set of soil conditions and are listed in Table 4. For these calculations an average normal load of 6174 N was used. Tire contact areas are as listed in Table 2.

The values from the first two test sets (16 and 17 March) are quite different from the rest of the values and were obtained using tire D. They also are the very first set of tests and are, therefore, more likely to have suffered from problems with the experimental procedure. For consistency, only the

Table 4. Values of c and φ; these are calculated based on the average peak traction from several tests for both the left and right wheels.

Test date (1988)	c		φ	
	Left (kPa)	Right (kPa)	Left (degrees)	Right (degrees)
16 Mar	160.5	130.9	−12.6	−6.2
17 Mar.	98.5	65.5	2.6	13.2
4 May	22.7	32.4	24.8	22.1
5 May	22.0	2;.8	22.1	21.5
18 May	41.3	33.8	15.7	18.6
9 Jun	25.5	10.3	25.3	30.0
10 Jun	23.4	−1.4	26.7	32.4
19 Jul	0.0	12.4	32.5	30.6
20 Jul	2.1	−12.4	31.4	36.7

Figure 12. Tractive coefficient increases with soil moisture content over the range of moisture contents tested to date.

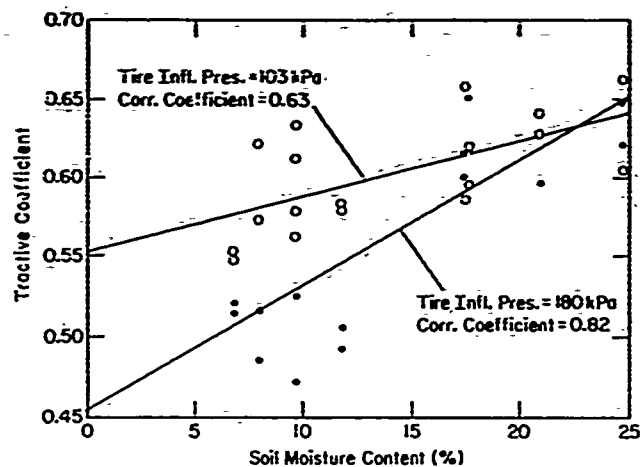parameters calculated using tire A are considered in the following analyses.

The c and φ values calculated using tire A are typical of sandy silts. They also compare with values obtained from laboratory strength tests on this soil: φ ranges from 17 to 34° and c is between 0 and 38 kPa. The soil is basically frictional, with some small amount of cohesion, or apparent cohesion, particularly at the lower moisture contents. The higher values of c are most likely attributable to capillary tension generated within the soil when moisture content is low. The negative values are physically meaningless and are merely caused by the need for very high accuracy of the instruments when cohesion is near zero.

The strength parameters are actually measured in the thawed soil zone but both the cone penetrometer and c and φ (as measured with the vehicle) inherently incorporate the effect of the frozen soil layer. The depth of the thaw, therefore, influences these values. Soil moisture content and density also affect soil strength, as discussed later.

Vehicle performance

The data were analyzed to investigate the relationships between the mobility characteristics and the soil parameters. The mobility characteristics used for comparison are the peak (net) tractive coefficient and the average motion resistance coefficient as listed in Table 3. The soil parameters used in the correlations were the thaw depth, density and moisture content, as well as the soil strength parameters, CI and CG from the cone penetrometer and c and φ, as measured with the instrumented vehicle.

Of the soil parameters measured, moisture content has the most influence on the traction of the vehicle. Figure 12 shows the relationship between tractive coefficient and moisture content for two contact pressures. Traction tends to increase with an increase in the water content of the soil. This is largely because the soil friction φ increases with water content, as shown in Figure 13, and traction is strongly influenced by soil friction as indicated in eq 2. The trend is stronger for the higher contact pressure. The relationship between the tractive coefficient and thaw depth has a good deal more scatter as does the effect of the density. As the experimental design is completed, the influence of these parameters should become distinguishable.

The soil strength parameters, c and φ, were also compared to the traction measurements to see how well they correlated and to determine the nature of the relationship. There is a clear relationship between both c and φ and vehicle traction at high contact pressures (Fig. 14) and less so at lower contact pressures. Both contact pressures show that φ has a stronger influence on traction than c and this is supported by theories used to predict traction, whether they are derived from the Mohr–Coulomb criteria (eq 2) or similarly based yield criteria. The additional scatter in the data at lower contact pressures is, in part, caused by the nonlinear nature of a typical soil failure envelope (Fig. 15). On this hypothetical soil failure curve, σ, the normal stress, is the contact pressure of the wheel on the soil and τ, the corresponding shear stress at failure, is peak vehicle tractive stress. At high normal stresses σ_{high}, the slope of the failure curve is nearly constant, whereas at low normal stresses
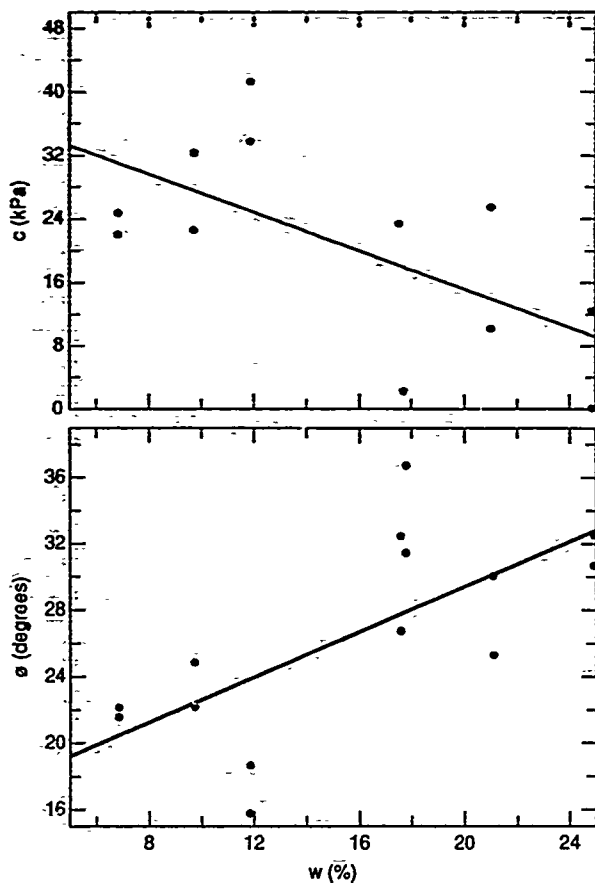
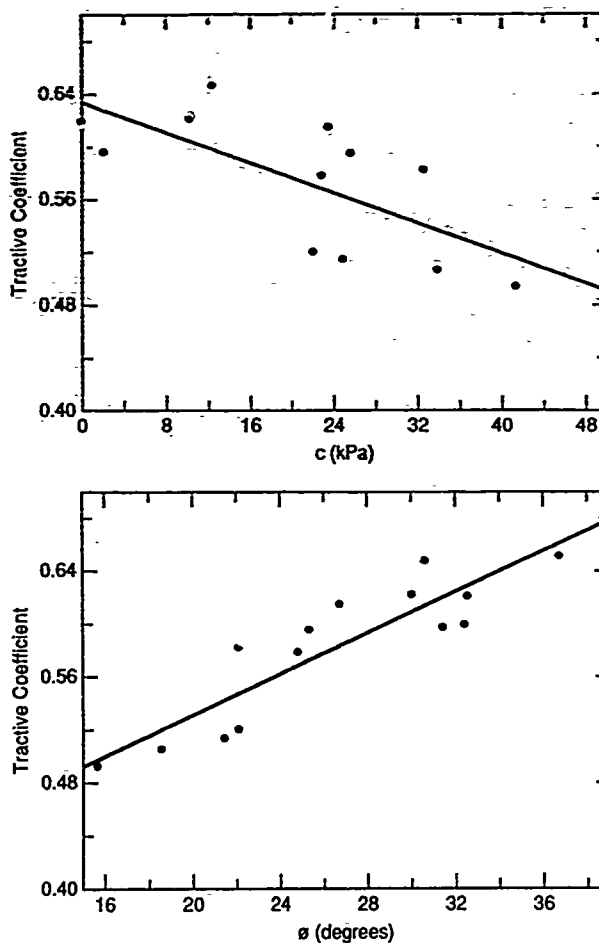*Figure 13. Relationship between soil strength parameters, c and ϕ, and moisture content.*

Figure 14. Relationship between tractive coefficient (at an inflation pressure of 179 kPa) and soil strength parameters, c and ϕ; negative values omitted.

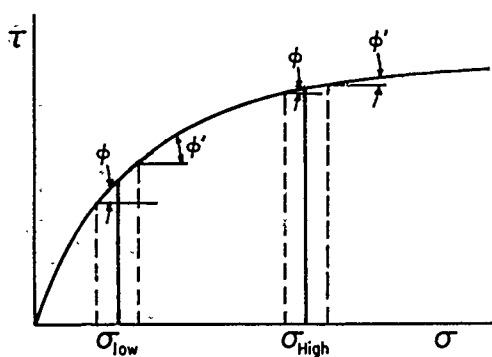*Figure 15. Typical soil failure envelope. A slight deviation in normal stress σ will result in a large variation in ϕ when σ is low. When σ is high, the same amount of deviation in σ causes only a slight variation in ϕ because the change in slope is more gradual.*
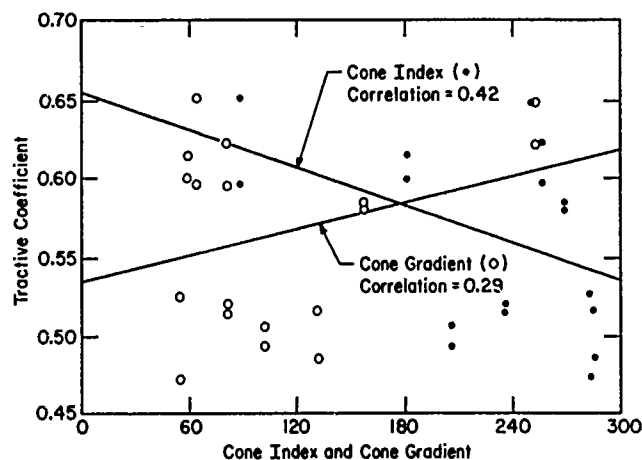

Figure 16. Relationship, or rather the lack thereof, between tractive coefficient and both cone index and cone gradient.

13

σ_{low}, the slope is changing rapidly. At σ_{low} a small variation in σ will intercept the failure curve at a wide range of slopes, and, therefore, result in more scatter in the calculated c and ϕ.

The peak tractive coefficient was graphed against cone penetration parameters, which also relate to soil strength. Both CI and CG were calculated. CI is generally used for cohesive soils and CG for noncohesive soils. The test soil is only slightly cohesive, depending on moisture content. A plot of CI and CG versus tractive coefficient for a tire inflation pressure of 179 kPa is shown in Figure 16. The data are very scattered and correlation is low for either linear or curvilinear regressions. Figure 16 shows the linear regressions (correlation coefficient is 0.42 for CI and 0.29 for CG). At a tire inflation pressure of 103 kPa (not shown) there is relationship between CI and traction (correlation coefficient = 0.05) and again only a slight trend showing traction increasing with an increase in CG (correlation coefficient = 0.39). Since an increase in cone parameters should coincide with an increase in traction, CG is the better indicator of vehicle performance for this soil. However, the very low correlation coefficients show that neither are adequate predictors. This is partly because of the limited range of conditions tested. The cone penetrometer is much better suited for distinguishing among a wide range of conditions to determine a *go* or *no-go* situation. In addition, the frozen soil layer strictly limits the use of the penetrometer to the soft, thawed soil. And while this layer is the cause of many mobility problems, its slippery nature when wet is not measured in the cone penetration test.

For the soil conditions tested to date, the measured motion resistance values are scattered and show no trends. Since the goal is to correlate motion resistance to soil properties, the data were further analyzed by "correcting" the resistance by subtracting the related hard surface motion resistance (listed in Table 3). This leaves only the forces caused by the interaction of the tire and the soil: bulldozing, compacting and relative tire–soil stiffness. Because hard surface motion resistance was not always measured, there is a relatively small number of data points and consequently we find no clear trends at this time.

SUMMARY AND CONCLUSIONS

1. An experimental test basin was designed and constructed to facilitate vehicle performance testing on freezing and thawing ground. The test basin was built in CRREL's FERF building and is unique in that field-scale testing can be conducted on carefully controlled and varied soil conditions regardless of the outdoor weather. To date, nine sets of soil conditions have been tested on a frost-susceptible silt. Soil conditions for these initial tests were dryer and stronger than originally anticipated. The next tests will include a water table in the basin (resulting in wetter and weaker thawed layers) and a trafficking series (to simulate multiple pass situations).

2. Our observations of many of the traction tests to date indicate that the initial tire slip (at low DIV) is caused by a failure within the soil itself and not at the tire–soil interface. As the tire spins faster and the DIV increases, the shear failure is at or near the tire–soil interface and the tire begins to dig down into the soil. This sequence of soil failure is caused by a progressive increase in the shear stress applied to the soil during a typical traction test.

3. At low water content, soil tension causes the soil to behave as a slightly cohesive material, which results in a peak in the traction curves occurring at low DIV (less than 0.6 m/s). At higher water content, the tractive coefficient reaches a maximum at 0.6 to 1.2 m/s DIV and remains at that level or drops only slightly as DIV increases. The thickness of the thawed layer also appears to influence the shape of the traction curve. When the tire quickly digs through the thawed soil, additional traction can be provided by the frozen soil, thus an asymptotic shaped traction curve.

4. The data from the cone penetrometer do not correlate well with the measured traction or motion resistance. This is probably because the penetrometer is best suited for distinguishing among a wider range of soil conditions. Also, the frozen soil layer restricts the use of the penetrometer to the thin thawing layer and the penetrometer is not suited to detecting the slipperiness of this layer.

5. Because of limited success with the cone penetrometer, soil strength was also calculated from data gathered with the instrumented vehicle. Using the forces measured at the tire–soil interface and the Mohr–Coulomb failure criteria, the soil strength parameters c and ϕ can be calculated. The c and ϕ measured are typical of a low plastic or nonplastic silt; c ranges from 0 to 38 kPa and ϕ ranges from 17 to 34°. It is likely that the small amount of cohesion present is merely apparent cohesion caused by increased soil tension at low moisture content.

6. Vehicle traction is most strongly influenced by soil moisture. This is because of the close link between soil moisture and the soil friction angle ϕ and the mechanical dependence of traction on ϕ (eq 2). Traction increases as ϕ increases. The traction is

14

also influenced by soil density and thaw depth but these effects are interrelated and confusing when viewed individually. The nature of the relationships among these parameters will be clearer when the experimental design is complete. The effect of the soil conditions on motion resistance is much more subtle and is not clear at present.

FUTURE DIRECTION

Experimental

The soil conditions created in the experimental test basin cover only a portion of the experimental design. The wetter and less dense conditions have been more difficult to create. Future freezing cycles will include a water table in the test basin. A water table will provide a source for moisture migration to the freezing front, causing ice lensing and frost heaving and, subsequently, saturated and supersaturated thawing conditions. In addition, after testing on the undisturbed soil, the area will be trafficked and then traction and motion resistance will again be measured. The trafficking series will also help vary soil conditions. After testing on the silt is completed, a response surface analysis can be performed and the test soil will be replaced by a more clayey soil for similar testing.

Soil strength

Preliminary analysis indicates that cone penetration does not correlate with vehicle mobility on thawing soils and, therefore, prediction schemes based on cone penetration are of little use. In pursuit of a more mechanistic method of relating vehicle mobility to thawing terrain, soil strength parameters calculated using the CIV must be validated for use in a model. For this reason, there will be an additional set of traction tests run at another tire inflation pressure. In addition, a weight will be placed on one side of the vehicle to alter the normal load on one wheel. This will result in a total of six independent measurements of traction (two distinct normal loads for each of the three inflation pressures). With the additional data points, more sophisticated traction equations and failure criteria can be developed and evaluated.

At the same time, the soil strength will be measured in the laboratory using both direct shear and triaxial compression tests and a shear annulus device will be used prior to each vehicle test series to characterize the soil conditions in situ. The soil strength parameters c and ϕ thus obtained will be compared with the values calculated from the vehicle data.

Theoretical

The interaction between the soil and the tire is very complex. The stress field is three-dimensional and dynamic and the actual traction mechanism was observed to change with soil conditions and tire slip. This type of complicated behavior is well suited for numerical modeling where tire and soil parameters can be changed quickly. Therefore, a numerical model will be used in the analysis of the experimental data. A finite element mobility model written by Yong et al. (1984) has been obtained as a starting point. In addition, the test conditions presented here are currently being simulated using a finite difference plasticity model written by Karafiath and Nowatzki (1978) and results will be used to calibrate the model.

LITERATURE CITED

Abele, G., J. Brown and M.C. Brewer (1984) Long-term effects of off-road vehicle traffic on tundra terrain. *Journal of Terramechanics*, 21(3):283–294.

Alkire, B.D., and J. Jashimuddin (1984) Changes in strength of silt due to freeze-thaw. *Journal of Technical Topics in Civil Engineering*, 110(1):48–53.

Allen, H.S., and D.L. Bullock (1987) Evaluation of deflection data as criteria for the posting and removal of spring load limits. *Fourth International Conference on Low-Volume Roads, Cornell University, Ithaca, New York, August, 1987.* Vol. I, p. 140–145.

Blaisdell, G.L. (1983) The CRREL instrumented vehicle. USA Cold Regions Research and Engineering Laboratory, Special Report 83-3.

Blaisdell, G.L., E.J. Chamberlain and M. Mellor (1987) Evaluation of the cold regions aspects of mobility and hardening of the mobile test bed at Malmstrom Air Force Base. USA Cold Regions Research and Engineering Laboratory, Contract report to U.S. Air Force, Ballistic Missile Office.

Burt, G.R. (1971) Travel on thawed tundra. *Proceedings of Symposium on Cold Regions Engineering, University of Alaska*, p. 296–319.

Chamberlain, E.J., M. Mellor and G. Abele (1988) Frozen ground strength characterization and grouser cutter design for hardening. In Transition and mobility over snow covered terrain for the mobile test bed. USA Cold Regions Research and Engineering Laboratory, Contract report to U.S. Air Force, Ballistic Missile Office.

Johnson, T.C., D.M. Cole and E.J. Chamberlain (1978) Influence of freezing and thawing on the resilient properties of a silt soil beneath an asphalt pavement. *Proceedings, Third International Confer-*

ence on Permafrost, Alberta, Canada, July 1978, p. 662–668.

Karafiath, L.L. (1975) Development of mathematical model for pneumatic tire–soil interaction in layered soils. U.S. Army Tank Automotive Command, Technical Report 21209 (LL152).

Karafiath, L.L., and E.A. Nowatzki (1978) Soil mechanics for off-road vehicle engineering. Clausthal, Germany: Trans Tech Publications.

Mikhailov, G.D., and G.P. Bredyuk (1966) Shear strength of clayey ground during thawing (according to laboratory and field studies). Materials of the 8th All-Union Interdepartmental Conference on Geocryology (Cryopedology), USSR Academy of Sciences, Siberian Department Cryopedology Institute, No. 5, p. 51–60. USA Cold Regions Research and Engineering Laboratory, Translation TL265.

Nixon, J.F., and A.J. Hanna (1979) The undrained strength of some thawed permafrost soils. *Canadian Geotechnical Journal*, **16**:420–427.

Radforth, J.R. (1972) Analysis of disturbance effects of operations of off-road vehicles on tundra. Muskeg Research Institute, University of New Brunswick, ALUR 71-71-13.

Radforth, J.R., and A.L. Burwash (1973) Transportation. In *Muskeg and the Northern Environment in Canada*, Chapter 10 (Radforth and Brawner, Eds.), p. 249–263.

Rickard, W.E., and J. Brown (1974) Effects of vehicles on arctic tundra. *Environmental Conservation*, **1**(1).

Rutherford, M.S., J.P. Mahoney, R.G. Hicks and T. Rwebangira (1985) Guidelines for spring highway use restrictions. Washington State Transportation Center Final Report WA-RD 80.1, FHWA-RD-86-501.

Shoop, S.A. (1988) Research plan and experimental design for the study of vehicle mobility on thawing soils. USA Cold Regions Research and Engineering Laboratory, Internal Report 1001 (unpublished).

Swanson, G.D., and T.R. Patin (1975) Small-scale mobility tests in fine-grained layered soils. USA Engineer Waterways Experiment Station, Technical Report M-75-1.

Wiman, L. (1982) Relationship between type and condition of soil in the subgrade and the dynamic *e*-modulus (mean modulus) of the soil during different seasons of the year. National Road and Traffic Research Institute (VTI), Sweden, NR 308 (abstract in English).

Yong, R.N., E.A. Fattah, and N. Skiadas (1984) *Vehicle Traction Mechanics*. New York: Elsevier.

Zhiquan, T. (1983) In-situ direct shear tests at the freeze/thaw interface and in thawed soils. *Proceedings 4th International Permafrost Conference, Fairbanks, Alaska*, p. 1278–1282.