ERDC/GSL SR-13-2

Geotechnical and Structures Laboratory

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Procedures for One-Pass Vehicle Cone Index (VCI_1) Determination for Acquisition Support

Maria T. Stevens, Brent W. Towne, George L. Mason,
Jody D. Priddy, Javier E. Osorio, and Clint A. Barela

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Final report

Prepared for Joint Program Office - Joint Light Tactical Vehicles (JPO-JLTV), Selfridge Air National Guard Base, MI 48045

Abstract

This report describes test procedures used to measure the minimum soil strength necessary for a vehicle to consistently complete one pass successfully (one-pass Vehicle Cone Index, VCI_1). The VCI_1 is a vehicle performance metric used to quantify mobility on soft soils. The report scope covers the specific procedures that should be used for evaluations in support of ground vehicle acquisition. The procedures define site selection criteria, test lane layout, soil data collection procedures, and analysis methodology to determine the VCI_1. Rationale behind the test procedures and detailed descriptions of the principal soil strength measurement techniques are provided in supporting appendices.

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Preface

The documentation of the test procedures reported herein was conducted between September 2011 and June 2013 by staff members of the US Army Engineer Research and Development Center (ERDC) in support of the Joint Program Office - Joint Light Tactical Vehicles (JPO-JLTV). The documentation effort was accomplished and this report was written by Maria T. Stevens, Brent W. Towne, George L. Mason, Jody D. Priddy, Javier E. Osorio, and Clint A. Barela of the ERDC Geotechnical and Structures Laboratory (GSL), Engineering Systems and Materials Division (ESMD), Mobility Systems Branch (MSB).

Randolph A. Jones was Chief, MSB; Dr. Larry N. Lynch was Chief, ESMD; Dr. William P. Grogan was Deputy Director, GSL; and Dr. David W. Pittman was Director, GSL.

COL Kevin J. Wilson was Commander of ERDC when this report was written. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (force)	8,896.443	newtons
yards	0.9144	meters

1 Introduction

Background

The ability of ground vehicles to traverse soft-soil terrain without becoming immobilized is important for operating in off-road environments. To quantify which vehicles perform better in this regard, it is necessary to consider the minimum soil strength necessary for a vehicle to cross the soil successfully. Those vehicles able to successfully traverse the weakest soils are the best soft-soil performers.

To date, the only direct metric for soft-soil performance of ground vehicles is the Vehicle Cone Index, or VCI. VCI quantifies the minimum soil strength required for a vehicle to consistently make a specified number of passes. Consideration is most often given to one-pass (VCI_1) and 50-pass (VCI_{50}) soil strengths.

VCI for a specific vehicle configuration is measureable from field testing and may also be predicted based on vehicle characteristics. Furthermore, it allows direct comparison between various vehicles regardless of the type of traction elements employed (e.g., the VCI of tracked vehicles can be directly compared to that of wheeled vehicles; Priddy and Willoughby, 2006).

Measurement of the minimum soil strength required for vehicle mobility was initiated by the US Army Corps of Engineers (USACE) in 1945 to address mobility issues observed during World War II. Although a standard methodology has been developed and used within the Corps of Engineers for decades, it has not been well documented and readily available to other potential soft-soil mobility evaluators. This document defines the standard test operating procedures developed by USACE to measure VCI_1.

The minimum soil strength required for vehicles to consistently make a specified number of passes can be measured on any soil type. Therefore, the VCI metric for soft-soil performance can be used to assess vehicle performance on any soil type. The metric is simply the minimum soil strength required to prevent vehicle immobilizations due to a combination of excess sinkage and total loss of net driving traction, and it is measured using straight-line vehicle trafficking on level-terrain soil with normal, non-slippery surface conditions.

The general procedures described herein can be used on any soil type, but the details of the described methods are most directly applicable for fine-grained soils. Additional procedures and soil measurements should be used for coarse-grained soils, but those procedures are beyond the scope of this report. Due to the specific goals of this report, it focuses strictly on the procedures and soil measurements for a single type of fine-grained soil.

The focus is placed on a single fine-grained soil type because vehicle performance on soft soil is influenced by the type of soil, such that higher soil strengths are required for vehicles to operate on some soil types relative to others. The cone penetrometer-based soil strengths required to operate on high plasticity clay soil (CH) are higher than for any other fine-grained soil type, making CH soil the worst case from a vehicle mobility perspective. Therefore, the VCI_1 database of performance measurements for fine-grained soils, which USACE has developed over the past five decades, has been predominantly focused on CH soil.

All fine-grained VCI_1 measurements conducted by USACE to support development of modeling and simulation for force projection and for evaluations to confirm requirements in vehicle acquisition have been restricted exclusively to CH soil. For vehicle acquisition, testing on CH soil ensures that vehicles can operate on the specified soft-soil conditions for any fine-grained soil type. For additional background behind the soil type and other standards for VCI_1 testing, refer to the rationale provided in Appendix A.

Purpose

The purpose of this study is to define test procedures used to measure the one-pass vehicle cone index (VCI_1) for vehicle acquisition purposes.

Scope

This report describes the specific procedures for measuring VCI_1 to support vehicle acquisition. The report does not provide a comprehensive coverage of all the kinds of soft-soil testing that may be considered for terramechanics research, nor does it describe all of the soil test procedures applicable for measuring VCI_1 in all soil types. Testing for vehicle acquisition is conducted on the worst case fine-grained soil type from a vehicle mobility perspective, and therefore, the report focuses on the procedures specific to CH soil.

Definitions

The following are definitions of specialized terms used in this report:

1. *Coarse-grained soil*. A soil containing 50% or less material smaller in diameter than 0.074 mm (No. 200 US standard sieve) (Meyer et al. 1977).
2. *Cone Index (CI)*. An index of soil shear strength obtained using a trafficability cone penetrometer standardized at the US Army Engineer Waterways Experiment (WES).
3. *Critical Layer*. A layer of soil lying below the natural terrain surface that exerts the greatest influence on trafficability.
4. *Fine-grained soil*. A soil containing more than 50% material smaller in diameter than 0.074 mm (No. 200 US standard sieve) (Meyer et al. 1977).
5. *Mobility*. The overall capability of a vehicle to move from place to place while retaining its ability to perform its primary mission (Meyer et al. 1977).
6. *Moisture Content (gravimetric)*. Ratio of the weight of water over the weight of solid particles in a mass of soil, normally expressed as a percentage.
7. *Rating Cone Index (RCI)*. An index of soil shear-strength that includes consideration of the sensitivity of soil to strength losses under vehicular traffic. It is defined as the product of Cone Index (CI) and Remold Index (RI) for the particular layer of soil.
8. *Remold Index (RI)*. An index of the sensitivity of soil to strength losses under vehicular traffic obtained using remolding equipment standardized at WES.
9. *Rut depth*. Residual sinkage; the depth of the rut (from original surface to bottom) in a vehicle path (Meyer et al. 1977).
10. *Sinkage (instantaneous)*. The depth to which the traction elements penetrate the terrain, measured normal to the original, undisturbed surface.
11. *Slip (travel reduction)*. An indication of how the speed of the traction elements differs from the forward speed of the vehicle. Slip is defined by the equation (Meyer et al. 1977):

$$i = \frac{r_R\omega - v}{r_R\omega}$$

where:

i = slip
r_R = rolling radius
ω = angular velocity of the wheel, or number of revolutions per unit time divided by 2π for a track
v = forward velocity of vehicle or wheel axle

12. *Trafficability*. The ability of terrain to support the passage of vehicles (Meyer et al. 1977).
13. *Unified Soil Classification System (USCS)*. A system that identifies (classifies) soils according to their textural and plasticity qualities and to their grouping with respect to their performances as engineering construction materials (Meyer et al. 1977).
14. *Vehicle Cone Index (VCI)*. The minimum soil strength required for a vehicle to consistently make a specified number of passes. Consideration is most often given to one-pass (VCI_1) and 50-pass (VCI_{50}) soil strengths.

Acronyms

The following are specialized acronyms used throughout this report:

ASTM	American Society for Testing and Materials
CI	Cone Index
ERDC	Engineer Research and Development Center
GVW	Gross Vehicle Weight
RI	Remold Index
RCI	Rating Cone Index
USCS	Unified Soil Classification System
USACE	US Army Corps of Engineers
VCI	Vehicle Cone Index
WES	Waterways Experiment Station

2 Test Procedures

Studies conducted in soft-soil trafficability (Nuttall et al., 1966; Schreiner, 1971; WES 1947-1974) show that mass soil-strength, quantified in terms of trafficability cone penetrometer and remold index measurements, closely relates to a vehicle's ability to negotiate soft soils. History and rationale behind the test procedures are discussed in Appendix A. Details of the cone penetrometer and its use are provided in Appendix B. Details regarding remold index testing are provided in Appendix C.

Vehicle parameters

The measured VCI_1 should represent only one configuration of the vehicle being tested. Key vehicle parameters, such as vehicle weight and tire pressure, should be maintained at constant values during testing.

For acquisition support testing, it is recommended that vehicles be tested at the expected gross vehicle weight (GVW) and, for wheeled vehicles, at an appropriate soft-soil tire pressure. For wheeled vehicles with a central tire inflation system (CTIS), testing the vehicle at the mud/sand/snow tire pressure setting is recommended. For wheeled vehicles without CTIS, the standard cross-country tire pressure may be more representative of expected field operations.

Prior to vehicle testing, key vehicle parameters should be measured on a level, hard surface and recorded. Anticipated modeling relationships that may be used to predict the VCI_1 performance should be considered to establish the appropriate list of vehicle parameters to measure. For wheeled vehicles key parameters include: individual wheel loads, minimum ground clearance, tire pressure, tire deflection, and the nominal tire dimensions (diameter, section width, and section height, at a minimum). For tracked vehicles, key parameters include: track loads, minimum ground clearance, track shoe dimensions (width and pitch, at a minimum), number and dimensions of track road wheels, and the dimensions of the contact area between the track and the ground on hard surfaces (track width and length on ground). These parameters should be monitored periodically throughout the evaluation to ensure consistent results.

During testing, soil strength measurements are critical, but common vehicle performance measurements are optional. Thus, it is not necessary to instrument the vehicle for VCI testing. Optional instrumentation may include GPS-based vehicle speed, individual wheel speed encoders, track tension transducers, sinkage sensors, and suspension displacement transducers. However, additional vehicle instrumentation should be considered, dependent upon the powertrain torque distribution characteristics anticipated for the vehicle.

For VCI_1 measurements, it is assumed that all powered running gear on the vehicle will receive ample driving torque from the powertrain to fully mobilize the traction available from the soil at the vehicle-soil interface. If there are any concerns that ample torque will not be delivered to all of the powered running gear traction elements (i.e., wheels or tracks), instrumentation should be used to measure the applied torque distribution during the VCI_1 testing. Predictions for VCI_1 performance will require this torque distribution information for partially powered running gear.

Site selection

For VCI tests, naturally occurring off-road lanes must be used (see Appendix A for additional rationale on lane preparation and soil profile layering). The lanes should be located on flat, level, soft-soil terrain that provides a range of RCI soil strengths near the expected VCI_1 magnitude. Floodplains and swampy areas near large surface drainage features such as rivers and lakes typically provide good test sites. Lakebeds that fill and empty seasonally can also be appropriate. The soft-soil areas at the site must be large enough such that the vehicle is not trafficking in and out of depressions during the test (e.g., narrow drainage features such as ditches are not suitable).

Test lanes should be a minimum of two vehicle lengths long, relatively straight and level, and of relatively uniform consistency at the point of immobilization. The lanes should be free of large rocks, logs, tree roots, and any other debris that could influence the VCI_1 performance. Prior lane clearing by test crews is sometimes necessary to remove light debris visible on the ground surface. The lanes should also not contain any visible ruts from prior vehicle trafficking or other similar activities; instead lanes should be in a natural state shaped only by sedimentary processes.

For acquisition support testing, test lanes must be located in soil that classifies as CH (high plasticity clay) under the Unified Soil Classification System (USCS; ASTM, 2011). Per the background information in Chapter 1 (and Appendix A), CH soil is the worst case soil type for vehicle mobility in fine-grained soils (Nuttall et al., 1966). Testing on CH soil ensures that vehicles can meet the specified soft-soil performance requirement on any fine-grained soil type. It is also important that the soil has no visible sand content. Even small percentages of sand can skew the VCI_1 measurements to lower values.

Test supervisors must also pay attention to the surface moisture conditions of the test site when selecting and describing lanes. The soil must have appropriate moisture to achieve the necessary range of strengths near the expected VCI_1 (as indicated by cone penetrometer measurements). However, the ground surface must not have excess free water (e.g., from recent rainfall or flooding events). Free surface water will cause a loss of traction (and thus overall mobility; Willoughby et al. 1991) with a relatively lower amount of sinkage due to surface slipperiness effects, whereas VCI_1 testing seeks to quantify mobility losses due to excess sinkage associated with low soil strengths.

In summary, lanes should be:

1. In a natural, minimally disturbed off-road area.
2. Level.
3. Straight.
4. Free of rocks, logs, and other debris.
5. At least two vehicle lengths long.
6. Ranging in strength near the expected VCI1 value.
7. Composed of CH soil with minimal sand content.
8. Free of surface slipperiness effects.

Test lane procedure

The standard technique used to measure VCI_1 is through inference from zero- and multi-pass test data. For these tests, the self-propelled test vehicle will be driven at a slow, steady speed making one or more passes in the same tracks through the test lane until immobilization occurs. Refer to Appendix A for more background and rationale behind the standard vehicle operation (i.e., trafficking) procedures used for VCI testing.

The vehicle should be operated in the optimal configuration for off-road performance on soft soil. For most military vehicles, the optimal off-road configuration requires the transmission and transfer case to be locked in the lowest gear setting and for all of the running gear to be in a fully-powered, driven mode (e.g., all-wheel-drive). Locking differentials are highly beneficial for good performance in soft soil, and if available, they should be engaged. The objective is for all powered running gear traction elements (i.e., wheels or tracks) to receive ample driving torque from the powertrain to fully mobilize the traction available from the soil at the vehicle-soil interface, and significant slip (i.e., travel reduction) will be required at each traction element in order for this to occur.

For zero-pass immobilization tests, the vehicle will be operated in its lowest gear at a slow, steady speed (2-3 mph) in a straight line through the identified test area. Steady throttle will be applied until the vehicle becomes immobilized – defined as complete loss of forward movement. The vehicle will then be placed in reverse, and an attempt will be made to back out. If the vehicle does not move, this is the zero pass immobilization point.

For the multi-pass tests, the vehicle will make passes through the lane in its lowest gear at a slow, steady speed (2-3 mph) with the vehicle's running gear travelling through the same tracks. The vehicle will traffic forward through the lane for the first pass and traffic backwards, in reverse, for the second pass. Any potentially negative effects due to trafficking in reverse are negligible, since the dominant factor controlling VCI performance is the vertical contact pressure of the running gear bearing on the soil and producing sinkage (Priddy, 1999). Forward and backward passes are continued until the vehicle becomes immobilized. As with the zero-pass test, the immobilization point is the point where the vehicle can move neither forward nor backward. (Note that the number of passes used for analysis is the number of good passes; thus if a vehicle makes eight good passes and becomes immobilized during the ninth pass, this would be considered an 8-pass lane.)

The immobilization-pass number is recorded, and notes are made of any significant observations of vehicle performance or test abnormalities. Appropriate notes include anything unusual that may have influenced the performance on the lane such as: the possibility of surface slipperiness effects, the presence of water in the ruts, the presence of buried logs or other debris in the ruts, vehicle leaning to one side due to left-to-right differential sinkage, and the pass numbers associated with different degrees of underbody dragging on the soil. These notes are associated with the soil strength data collected near the immobilization. They will be used during the analysis phase to help determine whether certain lanes should be weighted lower or eliminated from the analysis.

Testing should be performed on a variety of test lanes covering a range of soil strengths, producing a range of performance from low (zero) to high (50) successful passes. Although the primary focus of VCI_1 testing is on one-pass vehicle performance, it is necessary to collect multi-pass data to characterize the upper-bound performance trend that indicates an increasing number of passes can be made with the vehicle configuration on increasing soil strengths. Typically five to ten zero-pass tests and an equal number of multi-pass tests are required to establish the soil strength required for the vehicle to consistently be able to make one pass.

A general sketch of the test area and the completed test lanes will prove useful for later analysis. Data collected at each test lane can be compared against neighboring test lanes' data. Optionally, a GPS unit or other mapping methods can be used to create a more precise map of the test site.

Soil data collection

The mass soil strength of the test lanes is characterized in terms of Rating Cone Index (RCI). As shown in Equation 1, RCI is defined as the product of cone index (CI) and remold index (RI). CI and RI data are collected for each test lane using a cone penetrometer and remolding equipment, respectively.

$$\mathrm{RCI} = \mathrm{CI} * \mathrm{RI} \tag{1}$$

Due to the high variability in soil strength in natural lanes, the soil sampling must be adequate to develop a representative average soil strength that relates well to vehicle performance. Cone penetrometer measurements can account for not only the spatial variability over the area of vehicle lanes but also the three-dimensional spatial variability that is captured by the penetration resistance profiles with depth (Priddy et al., 2012).

Figures 1 and 2 show the locations of these soil measurements. CI and RI readings should be measured near the point of immobilization but outside of the influence zone (disturbed soil) generated by the vehicle's wheels or tracks.

Figure 1. Spatial orientation of soil measurements (plan view).

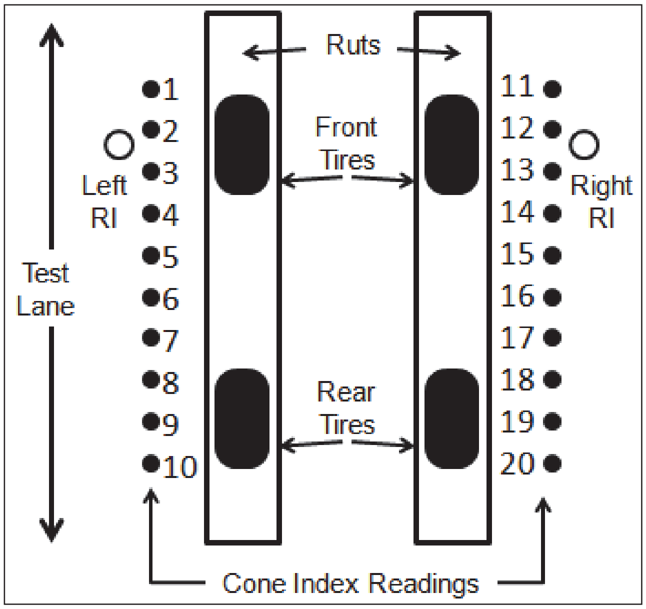
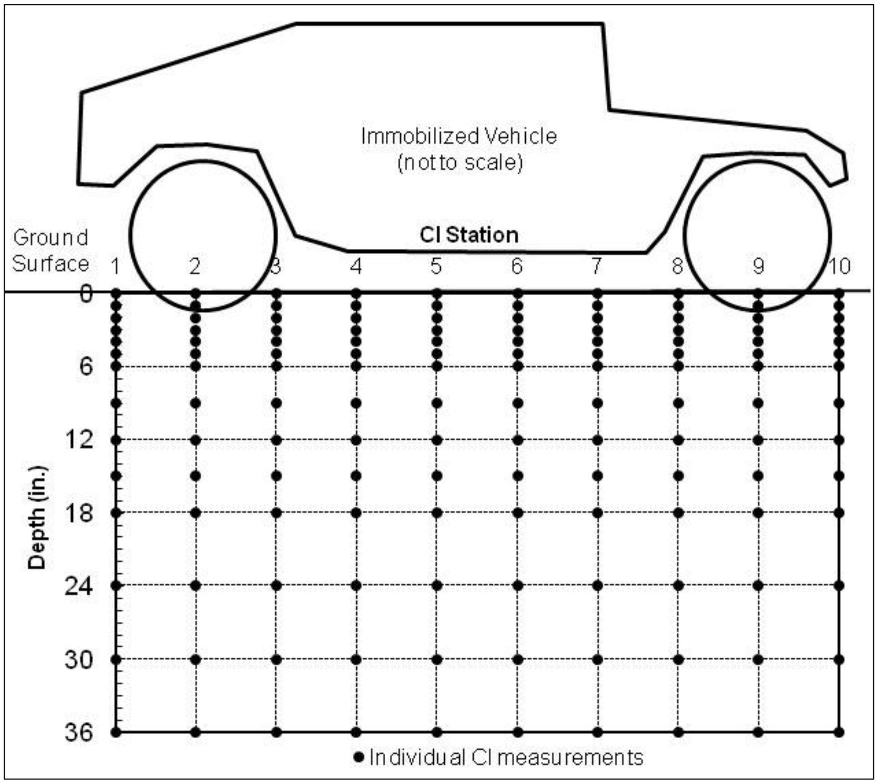
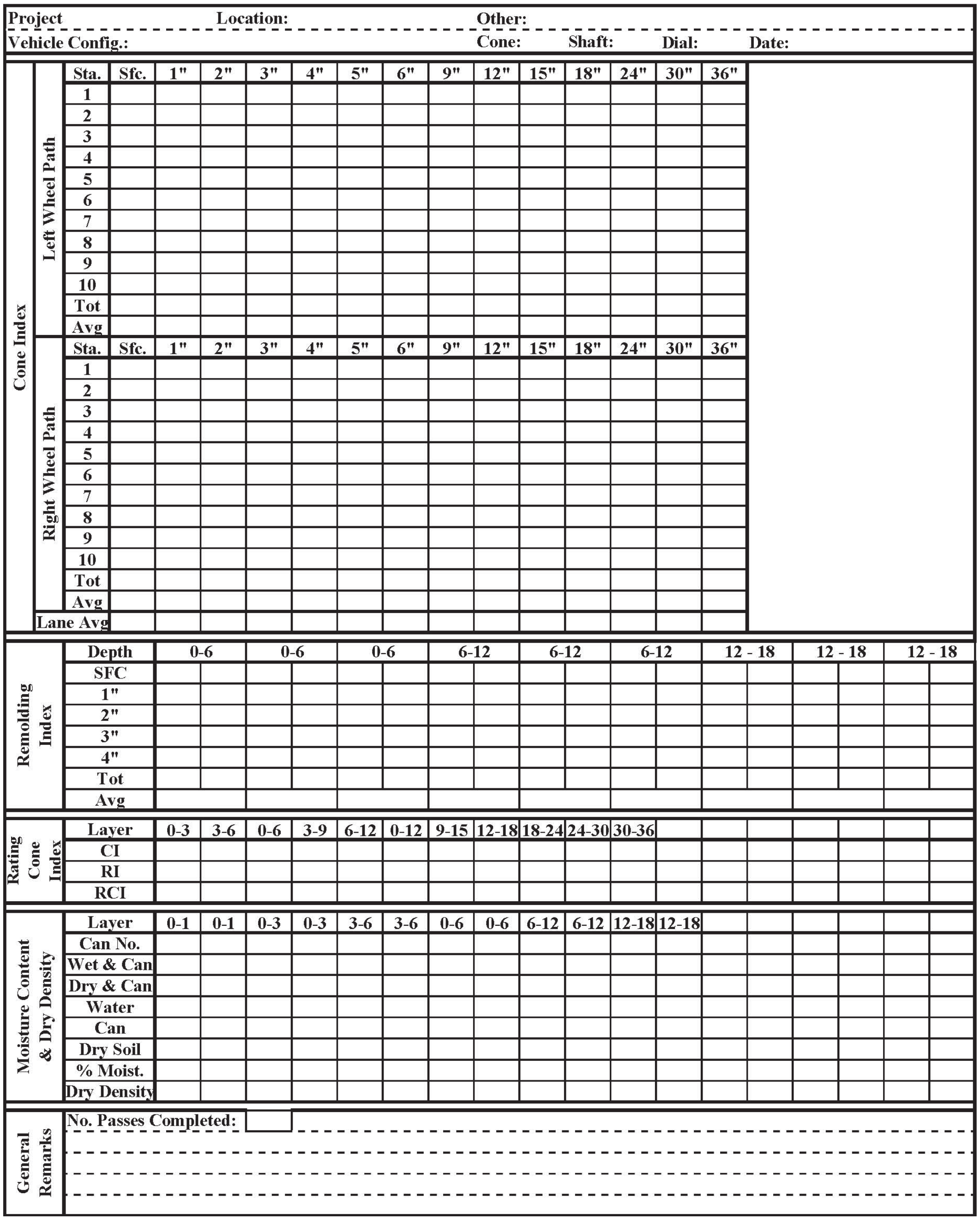


Figure 2. Locations of CI measurements (cross-section view).



All soil data should be recorded in a standardized format to ensure a consistent and complete record. Figure 3 shows the standard data collection sheet used at ERDC.

Figure 3. Standard VCI data collection sheet.



Project Location: Other:
Vehicle Config.: Cone: Shaft: Dial: Date:

		Sta.	Sfc.	1"	2"	3"	4"	5"	6"	9"	12"	15"	18"	24"	30"	36"
Cone Index	Left Wheel Path	1														
		2														
		3														
		4														
		5														
		6														
		7														
		8														
		9														
		10														
		Tot														
		Avg														
	Right Wheel Path	Sta.	Sfc.	1"	2"	3"	4"	5"	6"	9"	12"	15"	18"	24"	30"	36"
		1														
		2														
		3														
		4														
		5														
		6														
		7														
		8														
		9														
		10														
		Tot														
		Avg														
	Lane Avg															

	Depth	0-6		0-6		0-6		6-12		6-12		6-12		12 - 18		12 - 18		12 - 18	
Remolding Index	SFC																		
	1"																		
	2"																		
	3"																		
	4"																		
	Tot																		
	Avg																		

	Layer	0-3	3-6	0-6	3-9	6-12	0-12	9-15	12-18	18-24	24-30	30-36							
Rating Cone Index	CI																		
	RI																		
	RCI																		

	Layer	0-1	0-1	0-3	0-3	3-6	3-6	0-6	0-6	6-12	6-12	12-18	12-18						
Moisture Content & Dry Density	Can No.																		
	Wet & Can																		
	Dry & Can																		
	Water																		
	Can																		
	Dry Soil																		
	% Moist.																		
	Dry Density																		

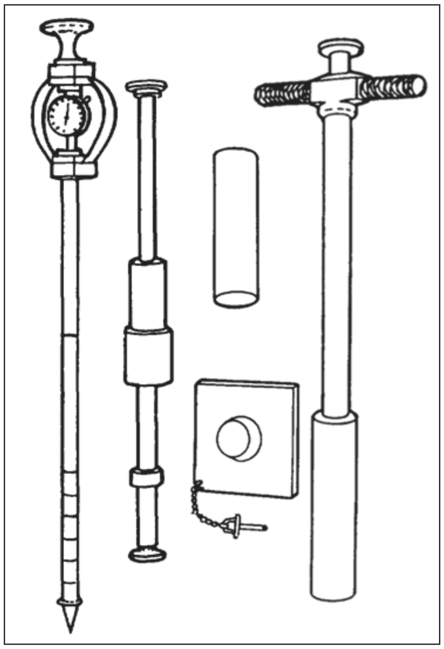
General Remarks

No. Passes Completed: ☐

Cone index

CI is an index of soil shear strength obtained via a standardized trafficability cone penetrometer (Freitag, 1968; Turnage and Freitag, 1969). The standard 300 psi dial cone penetrometer consists of a 30° cone of 0.5 sq-in. base area, an 18-in.-long rod that can be joined with other rods to provide an 18- or 36-in. length of rod, a proving ring, a dial gage, and a handle (Figure 4).

Figure 4. Soil equipment. From left to right: trafficability cone penetrometer, drop hammer, remold cylinder and base, and Hvorslev sampler.



When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. The stress (in psi) required to move the cone slowly (at a constant rate of approximately 0.1 ft/s; Turnage and Freitag, 1969) through a given plane is indicated on the dial inside the ring. This stress is an index of the shearing resistance of the soil and is called the CI of the soil in that plane. The range of the dial is 0 to 300 psi, and 300 psi is calibrated to a vertical applied force of 150 lb. The cone penetrometer can be fitted with a 750 psi dial using a 30° cone of 0.2 sq-in. base area to measure strengths in firmer soils. For more detail about the cone penetrometer and its use, see Appendix B.

The CI measurements are collected near the area of immobilization but outside the area of disturbed soil created by the vehicle passes. A minimum of ten CI measurements are collected along each side of the test lane, at least six of which must be taken immediately beside the immobilized vehicle (Figure 1), resulting in twenty CI measurements for each test lane. Additional CI measurements may be taken next to the test lane ruts behind the spot of immobilization.

While taking CI measurements, cone operators should observe that the CI is varying within a small range and either near constant or slightly increasing with depth. If atypical layers of unusually hard or soft soil are observed, the test supervisor needs to be notified so that a new testing area may be selected.

Cone operators should also inform the test supervisor if they notice a gritty feeling against the cone during the lane penetration measurements or during the remolding index measurements. This indicates that the test area may be too sandy for VCI testing.

Remold index

The RI is a measure of the sensitivity of soil to strength losses under vehicular traffic. RI is measured using remolding equipment (Figure 4), which consists of a Hvorslev sampler, a 2.5-lb drop hammer with a 12-in. drop, a cylindrical tube mounted to a base plate, and a cone penetrometer. For more detail about the remold kit and its use, see Appendix C.

Soil samples are taken from three different soil layers: surface to 6 in., 6 to 12 in., and 12 to 18 in. below the ground surface. If the 3-9 in. layer is of particular interest, soil samples may be taken directly from this layer, or the average RI between the surface to 6 in. and 6 to 12 in. layer may be used.

Undisturbed soil samples are placed in the cylindrical tube. Cone penetrometer readings are measured in the sample at the surface (where the base of the cone enters the soil) and at each successive inch to a depth of 4 in. Then the sample is remolded by subjecting it to 100 blows with the drop hammer. Cone penetrometer readings are performed on the remolded sample. The ratio of remolded strength to initial strength is the RI.

If the strength after remolding is greater than the initial strength, the RI is recorded as 1, rather than as a value greater than 1.

It should be noted if the hole from the first cone readings has not completely closed in the remolding process. In such cases, a new sample should be taken from a location adjacent to and at the same depth as the original. That sample can then be remolded and measured.

At minimum, RI should be measured on either side of the vehicle for each lane. If the RI measurements seem consistent with surrounding areas and with each other (within about 0.1), no further measurements are necessary. If the measurements do not agree, two additional measurements should be made, one on each side of the vehicle and not adjacent to the original two measurements.

Rating Cone Index

The RCI of any given test lane can be calculated for a particular soil layer of interest by taking the product of the average cone index and the average remold index in that soil layer.

Additional soil data

Additionally, it is necessary to confirm a consistent CH soil with low sand content, similar to the sample data shown in Table 1. Soil classification should be performed per ASTM (2009, 2011) standards regarding USCS. Natural moisture content and density of each 6-in. soil layer should also be sampled and recorded for each lane. One sample on each side of the test lane near the remold sample locations is sufficient.

Table 1. Example soil properties report from an acceptable VCI test site.

Description	LL	PL	PI	% Sand	% Fines	USCS
Lane 4, Depth 0-6"	69	27	42	0.9	99.1	CH
Lane 4, Depth 6-12"	62	23	39	0.5	99.5	CH
Lane 4, Depth 12-18"	65	24	41	0.3	99.7	CH
Lane 7, Depth 0-6"	79	30	49	1.2	98.8	CH
Lane 7, Depth 6-12"	72	26	46	0.7	99.3	CH
Lane 7, Depth 12-18"	68	25	43	0.7	99.3	CH
Lane 9, Depth 0-6"	77	30	47	0.6	99.4	CH
Lane 9, Depth 6-12"	63	24	39	0.4	99.6	CH
Lane 9, Depth 12-18"	71	26	45	0.3	99.7	CH
Lane 10, Depth 0-6"	74	25	49	2.4	97.6	CH
Lane 10, Depth 6-12"	67	26	41	0.6	99.4	CH
Lane 10, Depth 12-18"	74	24	50	0.3	99.7	CH

3 Data Analysis

The first step in data analysis is to aggregate the field data. Typically, soil strength is analyzed by 6-in.-thick layers; however, 12-in.-thick layers may also be considered. A test lane's RCI is computed for each layer of interest by multiplying the average of all CI measurements within the layer by the average of all RI measurements within the layer. This computed RCI should be rounded up to the next integer value (e.g., 28.3 will be rounded up to 29) to ensure conservatism in the analysis. VCI is not reported with greater than integer precision.

Table 2 shows sample RCI data.

Table 2. Sample data for VCI analysis.

Lane No.	Passes Made	Layer Cone Index (CI)				Layer Remold Index (RI)			Layer Rating Cone Index (RCI)				Critical Layer RCI
		3-9	6-12	9-15	12-18	0-6	6-12	12-18	3-9	6-12	9-15	12-18	6-12
1	15	43	47	50	51	0.83	0.71	0.60	34	34	33	31	31
2	9	42	42	42	43	0.83	0.71	0.60	33	30	28	26	26
3	0	31	32	32	33	0.64	0.65	0.65	20	21	21	22	21
4	6	43	44	43	43	0.64	0.66	0.69	28	30	29	30	30
5	7	40	42	41	44	0.64	0.66	0.69	26	28	28	31	28
6	1	34	37	40	40	0.62	0.66	0.64	22	25	26	26	25
7	0	32	35	35	35	0.62	0.66	0.64	21	24	23	23	23
8	3	39	42	41	43	0.62	0.66	0.62	25	28	27	27	27
9	16	48	56	61	62	0.88	0.71	0.73	38	40	44	46	40
10	25	49	53	56	59	0.71	0.71	0.73	35	38	41	44	38
11	0	36	43	45	46	0.66	0.73	0.59	25	32	30	28	28
12	0	29	35	39	41	0.63	0.69	0.50	20	25	24	21	21
13	0	31	36	39	41	0.63	0.69	0.50	21	25	24	21	21
14	8	53	59	63	62	0.66	0.76	0.68	38	45	46	43	43
15	40	61	65	65	65	0.78	0.78	0.72	48	51	49	47	47

Selecting the critical layer and applying the Drop Layer Rule

After all of the data have been aggregated, the next step toward determining VCI_1 is to determine the critical layer. The critical layer is the soil layer that has the greatest influence on the VCI_1 performance, and the soil strength value within the critical layer represents the VCI_1 performance measurement.

Intuitively, it may appear that the critical layer is the layer on which the vehicle is resting when it becomes immobilized. This is not the case. Although rut depth (permanent deformation) and sinkage (instantaneous deformation) are related to both soil strength and vehicle characteristics, methodology for determination of the critical layer does not use rut depth or sinkage measurements. This is because in a normal soil profile used for VCI testing, the vehicle will typically sink down through the critical layer. Location of the critical layer is more closely related to the critical depth of the sinkage mobilizing stress that occurs within the soil beneath the center of the running gear ground contact at the initiation of downward sinkage movement. Refer to Appendix A for more background and rationale behind the critical layer.

It is necessary to analyze various soil layers to determine which layer controlled the performance for the particular test dataset. Typically, the layers that are considered for this are 6-in. overlapping layers at the following depths (in inches below the undisturbed ground surface): 0-6, 3-9, 6-12, 9-15, and 12-18. Table 3, reproduced from Army FM 5-430-00-1 (1994 and revisions in preparation), shows the normal critical layer for various vehicle configurations. This table was developed primarily to aid rapid soil measurements during reconnaissance for military operations, and it shows the layers that are most commonly critical in relation to simple vehicle characteristics. The FM table should be used as a guide to determine the most likely critical layer based on past experience. However, the analysis of the layers takes precedence over the table since the critical layer may not be “normal”.

The critical layer exerts the most influence on vehicle performance. Therefore, it will produce the best trends indicating that increasing soil strength results in increasing vehicle passes prior to immobilization. It will also produce the best separation between go and no-go performance, which is the principal basis for determination of the critical layer. For each soil layer, a go/no-go separation chart is created (Figure 5) to evaluate possible critical layers.

Table 3. Normal critical layer based on vehicle type.

Type of Vehicle	Configuration	Critical Layer (inches)
Wheeled	Wheel loads under 2,000 lb	3-9
	Wheel load between 2,000 and 15,000 lb	6-12
	Wheel load over 15,000 lb	0-12
Tracked	Ground contact pressure less than 4 psi	3-9
	Weight less than 100,000 lb	6-12
	Weight over 100,000 lb	0-12

Figure 5. Sample go/no-go separation chart.

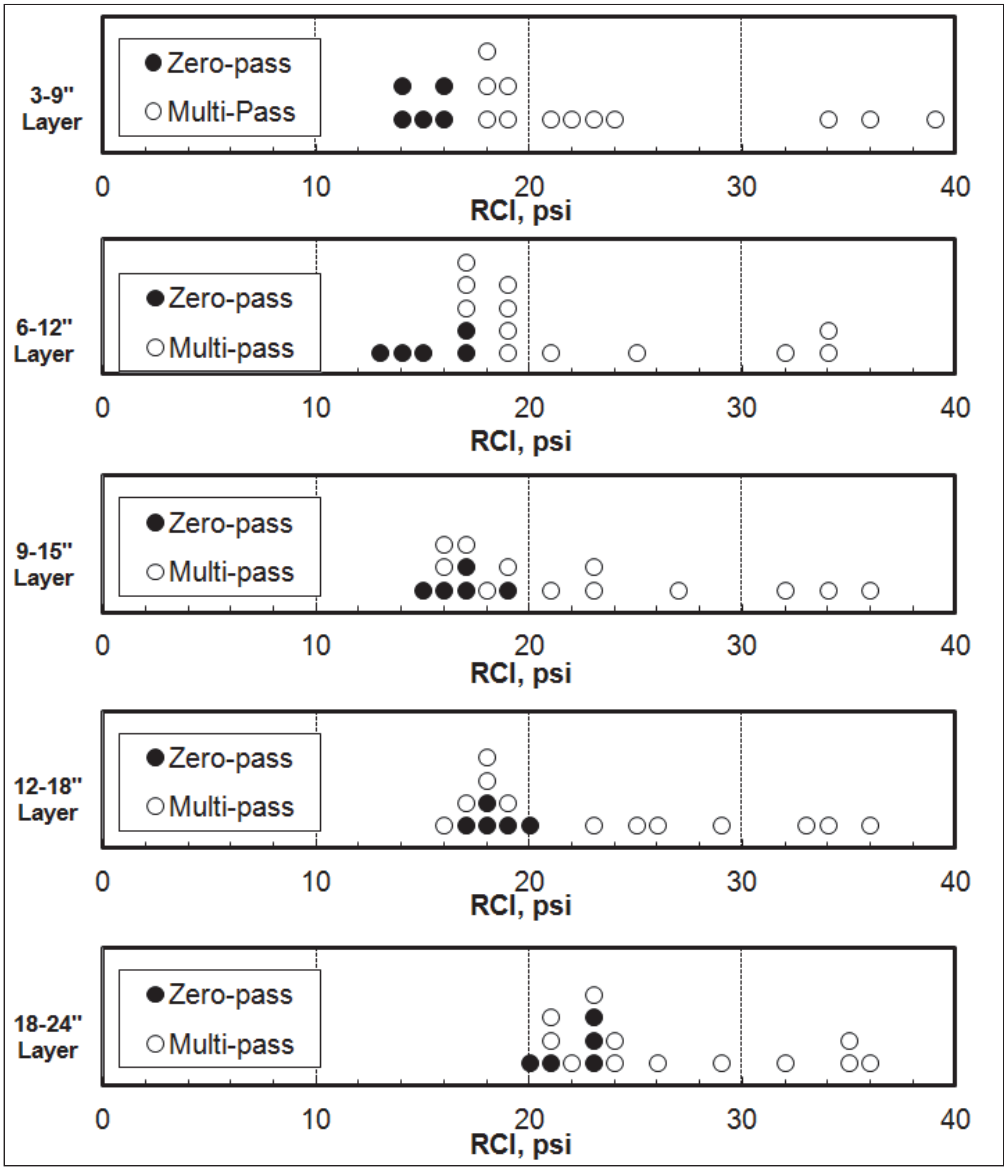
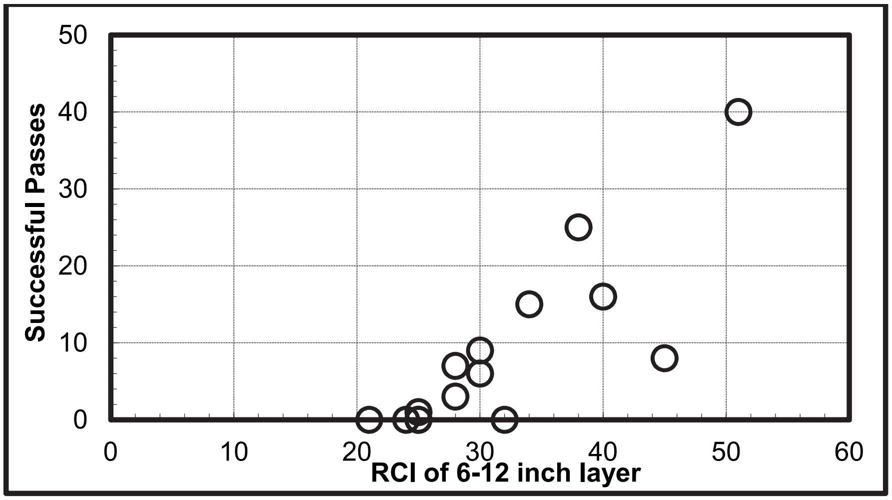


Figure 5 shows a notional dataset in which the 3-9 in. layer was selected as the critical layer because there was a clear separation between zero-pass (no-go) and multi-pass (go) test data. The 6-12 in. layer shows decent separation, but the high RCI zero-pass and the low RCI multi-pass tests overlap. The other layers in this dataset show poor go/no-go separation and would not be considered as potential critical layers.

Perfect separation between go and no-go data points seldom happens in practice. Therefore, the layers that produce the best go/no-go separation are analyzed further, and the normal critical layer (Table 3) is given precedence over other layers with similar quality in go/no-go separation. It is often found in the subsequent analysis that the projected VCI_1 measurement is essentially the same in each of the best candidate layers for the critical layer.

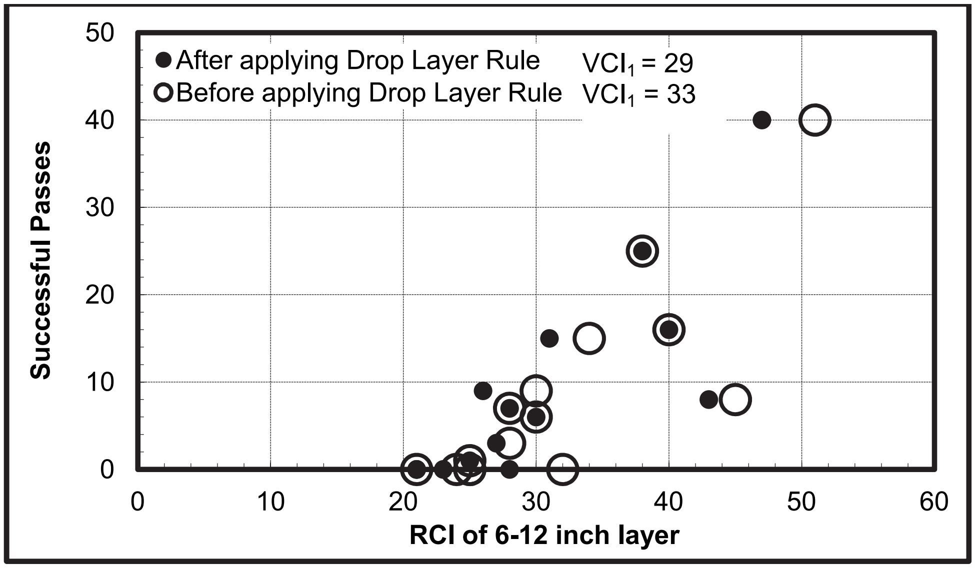
After one or more of the best layers have been chosen as potential critical layers from the go/no-go separation charts, a plot of number of successful passes versus soil strength (RCI) is created (Figure 6) for each potential critical layer.

Figure 6. Sample initial VCI plot.



For test points where the 6-in. layer below the potential critical layer is weaker, the weaker soil strength is used (Schreiner, 1971). For example, if the RCI value of the 12-18-in. layer for any given test lane is lower than the RCI value of the 6-12 in.-layer, the RCI value from the 12-18-in. layer is used. This rule is commonly referred to as the “Drop Layer Rule.” Figure 7 shows the influence of the Drop Layer Rule on the sample dataset. Without this rule, the VCI_1 in this dataset would be 33, but with the Drop Layer Rule, the VCI_1 was determined to be 29.

Figure 7. Sample dataset before and after the application of the Drop Layer Rule.



After applying the Drop Layer Rule, the critical layer for VCI_1 determination is selected as the soil layer with:

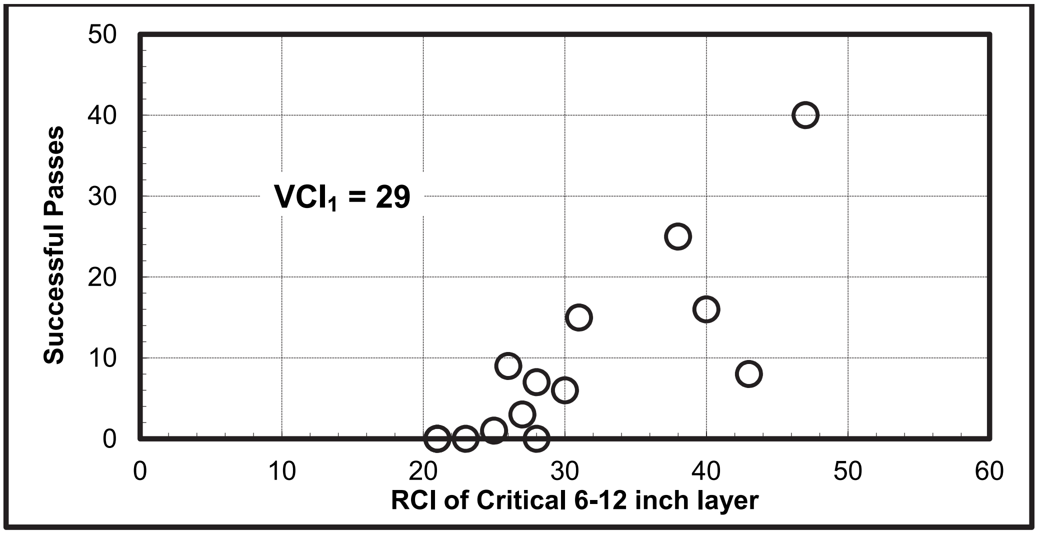
1. the clearest upper-bound trend in the VCI plot indicating increasing passes with increasing RCI, and
2. the best separation of go and no-go performance in the go/no-go separation chart.

VCI_1 determination

Once a critical layer has been selected with the Drop Layer Rule applied, a final plot of successful passes versus RCI of the critical layer (Figure 8) is used to determine the VCI_1. This is the RCI that appears to correspond to one pass based on the trend of the available data points. Often, the VCI_1 is determined by adding one to the RCI of the highest zero-pass lane. It is not uncommon for a low-pass lane to have a lower strength than the highest zero-pass lane. The key is that VCI_1 is the soil strength that will *consistently* allow one pass of the vehicle.

It should also be noted that occasionally a zero-pass lane is measured at an RCI value unexpectedly higher than a multi-pass lane (for instance, several RCI points higher than a 10-pass lane). In such cases, it is necessary to consider whether surface slipperiness effects or other factors may have skewed the results of this lane by referring to the notes recorded concerning potential test abnormalities observed during the test (as described in the Test lane procedure section of Chapter 2).

Figure 8. Sample final VCI plot using critical layer and the Drop Layer Rule.



The highest zero-pass lane in the sample dataset in Figure 8 underwent such scrutiny because it occurred at a soil strength higher than that of a nine-pass lane. However, there were no potential issues logged for this lane, implying that it is a valid test point. Consequently, it became one of the most crucial points to the dataset. This highlights the importance of high quality logging during the testing. It also demonstrates that it is beneficial to perform VCI analysis soon after the completion of field testing so that good decisions can be made concerning reduced weighting or elimination of suspect data points in the final analysis.

To ensure that the inferred VCI_1 measurements are interpreted in a consistent and repeatable manner for all vehicles tested over time, standard “rules” of analysis have been established. The “rules” for VCI_1 determination are as follows:

1. Remove suspect lanes from analysis, both during the field testing and in the office.
2. Use conservative RCI values by rounding up to the next integer value (e.g., 28.1 becomes 29).
3. Use the critical layer from FM 5-430-00-1 (1994) unless a different soil layer provides a clearly superior correlation.
4. Drop Layer Rule: Use the RCI of the critical layer unless the layer directly below it has a lower strength.
5. Scrutinize and potentially ignore zero-pass lanes that have measured RCI values higher than 10-pass lanes.
6. Define the VCI_1 measurement based on the highest, legitimate zero-pass RCI plus one, at a minimum.

Data quality

To further ensure reliable and repeatable results, special attention must be taken to analyze the soil data for outliers that may affect the determination of the VCI_1. In the go/no-go separation charts and the VCI plots, data points from some lanes may appear to be inconsistent with the overall data trend; each of those points should be scrutinized more closely.

It is expected that there will be scatter in the VCI plot due to natural variability associated with spatial and profile layering variations in the soil characteristics between lanes. Furthermore, the VCI plot represents a sparse dataset for practical reasons. Ideally, hundreds of data points (lanes) would be collected to define the boundary between go and no-go soil strengths for VCI_1 through VCI_{50} performance. However, this is not feasible due to time and budget constraints. Nonetheless, application of the standard “rules” of analysis to these sparse datasets has yielded consistent, predictable results over the past several decades (Priddy and Willoughby, 2006).

Data quality checks will not eliminate the soil’s natural variability. However, appropriate checks can be used to identify soil strength measurements (both CI and RI) that may be anomalous. Any measurements (or samples) that are confirmed to be unrepresentative for the test lane using appropriate checks should be revised based on nearby measurements or eliminated from the analysis.

Cone Index

The average CI profile with respect to depth should be analyzed to compare the profile between all of the lanes, as shown in Figure 9. It may be useful to break this analysis into separate charts, for example, one chart for zero- and low multi-pass lanes and another chart for high multi-pass lanes.

A normal soil profile is one in which soil strength is uniform or uniformly increasing with depth, similar to the profiles in Figure 9. While a normal profile is preferred in the top 36 in., it is not absolutely necessary, as the Drop Layer Rule can account for some variability of the soil profile. Nonetheless, inconsistent layers, foreign objects, or hard pans (Figure 10) may skew the data, particularly when present in the first 18 in. Lanes with severe anomalies should be removed from the analysis (refer to Appendix A for additional rationale on the soil profile layering).

Furthermore, the distribution of CI measurements between locations within a lane should be investigated for trends that may affect the test results.

For example, test lanes are often excluded from final analysis if the difference in strength between the right and left wheel paths is significant. This is usually noted in the field because a drastic left/right difference in soil strength may cause the vehicle to sink more on one side than the other. Thus, the vehicle may develop a notable lean toward the weaker side before it is immobilized. However, this is not always the case, so it is necessary to check for this trend during data analysis.

Figure 9. Sample cone index profile using average CI for each lane.

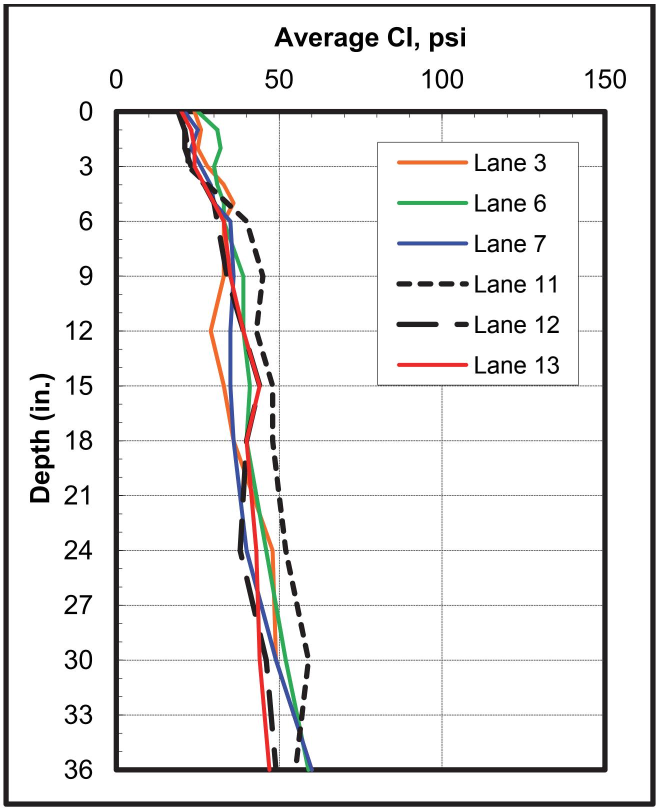
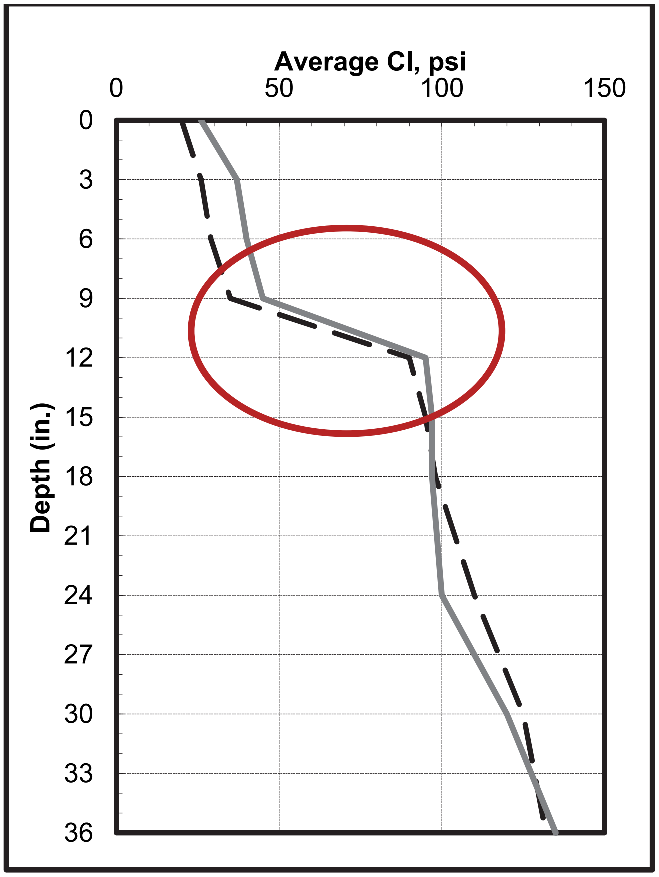


Figure 10. Sample CI profiles with hardpan.



For this application, it is often useful to create a CI depth profile for all of the individual measurement locations that have been averaged together for a particular lane (Figure 11). This raw data is usually not as clean looking as the lane averages CI profile. Interpretation can be aided by adding guiding trend lines for overall lane average, left and right rut averages, and standard deviations.

Despite how chaotic the profile in Figure 11 may appear, this test lane is an example of a good set of CI measurements. Nearly all of the data fall in a relatively narrow window. Furthermore, the left and right averages (Figure 12) are similar to the overall lane average; they also intersect, rather than consistently remaining to one side of the overall mean.

In contrast, the lane represented in Figure 13 shows an example of poor agreement in left/right soil strength; in this case, the vehicle would be likely to lean heavily to the left where soil strengths are significantly lower.

Figure 11. Sample cone index profile for all 20 CI measurements within a single lane.

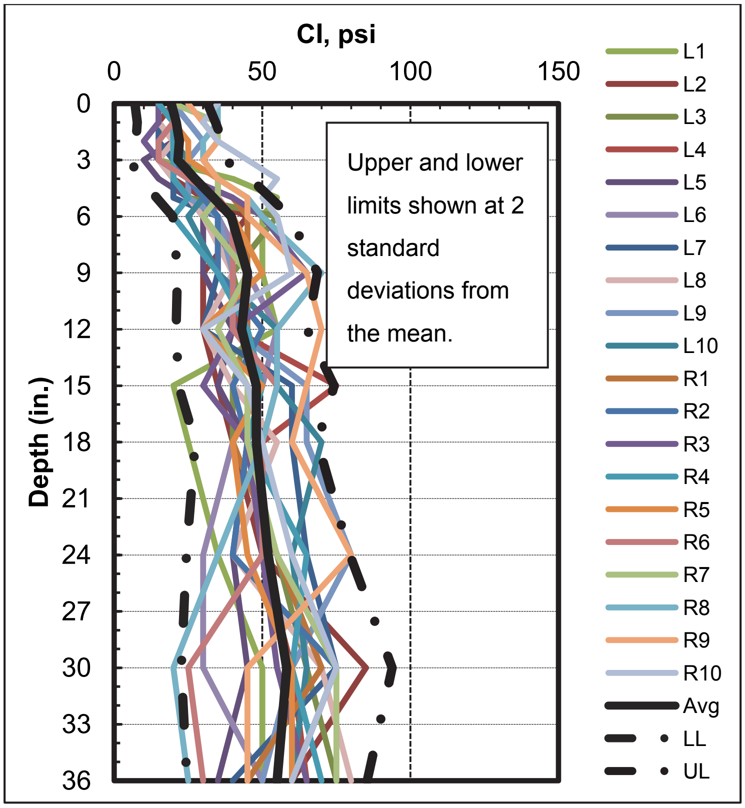


Figure 12. Example of good left/right agreement in CI.

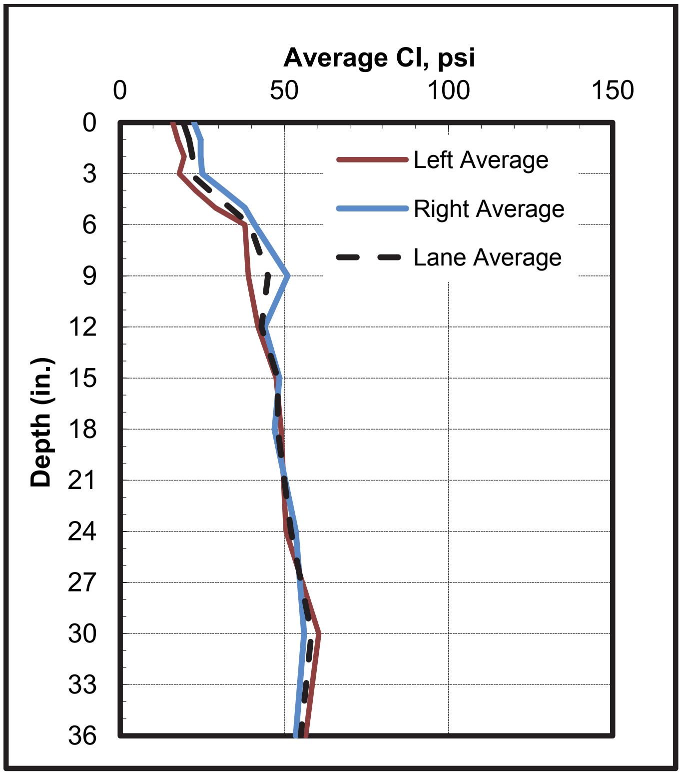
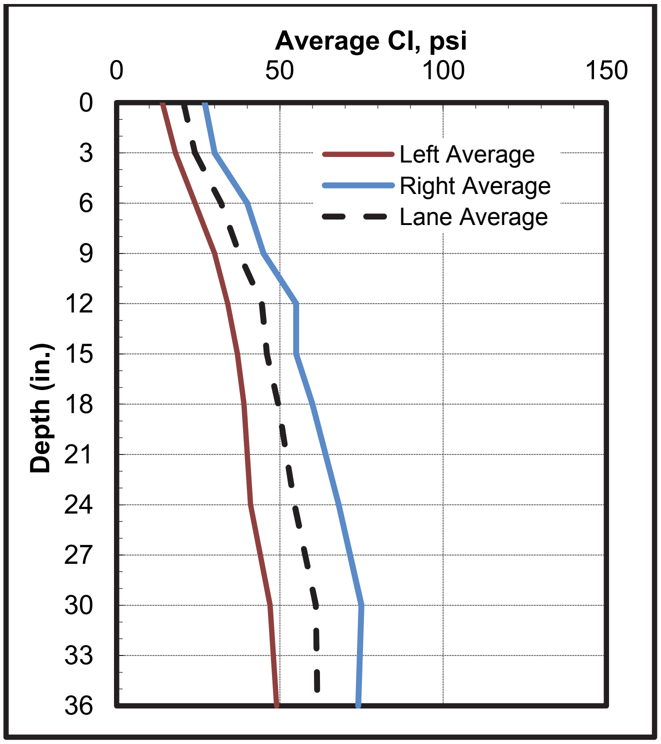


Figure 13. Example of poor left/right agreement in CI.



Remold Index

Just as the CI measurements must be scrutinized for unrepresentative data points, the RI measurements must also be reviewed. In a given dataset, it is expected that each individual RI measurement will be somewhat consistent with:

1. the overall RI distribution
2. the measurements in the different layers in the same lane, and
3. the measurements in the same layer in nearby lanes.

To check this, it is useful to compute average and standard deviation of RIs in these groupings. Those RI measurements that appear to be outliers can be replaced with representative values from nearby measurements.

Based on the analysis of Collins (1971), it is unlikely that a CH soil will exhibit an RI less than 0.5. This agrees with SME experience in VCI testing. Thus, it is recommended that any RI values less than 0.5 be scrutinized relative to the RI measurements from nearby lanes and other layers from the same lane. If the comparison indicates that the RI measurements may be unrepresentative for the lane, the RI value should be revised based on the other appropriate measurements, particularly if apparent discrepancies in the performance trends are removed or improved.

4 Conclusion

This report defines the standard procedures used to measure the minimum soil strength required for a vehicle to consistently obtain one pass in soft soil, or VCI_1. Because the VCI_1 soft-soil metric is used as an acquisition requirement, the procedures constrain testing to natural, straight, level, non-slippery, undisturbed test lanes composed of high plasticity clay (CH by USCS) soil. Testing on CH soil under these controlled, repeatable conditions ensures that vehicles can operate on the specified soft-soil conditions for any fine-grained soil type and for essentially all operational scenarios the vehicles may be required to carry out in their mission profile.

This report describes the standard test conditions, equipment, field procedures and analysis procedures as they have been established and practiced up until the time of publication. By increasing awareness of these procedures among the ground vehicle community, ERDC is hopeful that others will gain a better understanding and be able to appropriately use the standard USACE procedures for conducting VCI_1 performance measurements.

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Appendix A: Rationale and Evolution History behind the VCI Test Procedures

The VCI measurement test procedures developed by the US Army Corps of Engineers (USACE) (primarily between 1945 and 1974) evolved to serve *two principal motivators:*

1. **A battlefield command and control motivator (force projection)**. First and foremost, VCI was developed to provide a basis for preventing soft-soil immobilizations during military operations anywhere in the world.
1. **A vehicle acquisition support motivator.** Secondly, VCI was developed to produce consistent, repeatable data for which vehicle performance prediction methods could be developed that quantify the influence of vehicle characteristics on performance in soft soil.

The following rationale descriptions derive from various published references listed in the bibliography at the end of this appendix. All of the references would need to be read in chronological order in order to fully comprehend the evolution of the test procedures. Specific citations are provided in the text below for some of the key points. Some of the comments below do not originate from the statements made in the references, but instead were ascertained based on data from the references and/or observed changes in the utilized procedures over time (as reinforced by verbal input from USACE researchers that were directly involved in the evolution of the procedures).

Vehicle Operating Procedures

One key aspect of the VCI test procedures relates to the multi-pass vehicle operating procedures, or “traffic patterns.” The standard vehicle operating procedures (that is, driving slowly in a straight line forward and reverse through the same ruts) were developed to provide a consistent (as much as possible in soil) and conservative basis for evaluating soil trafficability.

USACE researchers also explored other vehicle operating procedures during the standardization of the test procedures (such as emergency stop and retreat maneuvers, straight-line with lateral offsets for overlapping staggered-track effects, and circular trafficking). The varied traffic patterns and other experience has confirmed that there are better ways to operate vehicles in soft-soil areas (e.g., staggering vehicle tracks rather than running through the same ruts can allow more vehicle passes, and going fast can allow momentum to aid crossing soft areas of limited extent).

However, the VCI test procedure does not attempt to replicate or define the best way to cross soft soil. Instead, it emulates a realistic manner in which military vehicles may have to cross soft-soil areas where they are constricted to narrow lanes and low speeds (battlefield command and control motivator). More importantly, the tests are conducted in a manner that is easily defined and repeatable, and as such, produce measurements that facilitate vehicle performance comparisons on a consistent basis (vehicle acquisition support motivator).

Soil Type

Another key aspect of the test procedures relates to the soil type. USACE researchers developing the VCI measurement and prediction methods determined that soil type has a significant impact on VCI measurements. They had originally hoped that Cone Index (CI) measurements would produce the same VCI numerical value (i.e., CI at threshold of immobilization) regardless of soil type. That was not the case, however, because cone penetrometer measurements alone do not sufficiently characterize the nature of the soil and its loading response.

The inadequacy of CI alone was realized early on in the USACE trafficability research for both prepared lanes (Anon. 1949c) and naturally occurring soils (Anon. 1954a). This observation led to the development of the Remolding Index (RI) soil test method and the Rating Cone Index (RCI) soil strength metric (where RCI = CI x RI). RCI became the standard soil strength metric for VCI field testing in fine-grained soils and remoldable sands (Anon. 1954a).

For 50-pass performance (VCI_{50}), RCI largely eliminated variation in VCI measurements for different fine-grained soil types; that is, researchers observed similar RCI at threshold of immobilization regardless of soil type (Anon. 1956; Kennedy and Rush 1968). That was not the case for one-pass performance (VCI_1) (Nuttall et al. 1966).

The realization that the RI method, which was standardized for VCI_{50}, did not eliminate the influence of soil type on VCI_1 performance ultimately led USACE researchers to reluctantly forgo pursuit of a soil strength metric that would produce the same VCI value for all soil types under all terrain conditions. They determined, however, that RCI was a better soil strength metric than CI for one-pass performance relations, which verified that there were significant advantages in using the RI method for both VCI_1 and VCI_{50} (Schreiner 1971).

USACE researchers determined that high-plasticity clay (CH) soil was the worst case for trafficability in fine-grained soils and remoldable sands, since RCI-based VCI_1 numerical values tend to be higher in CH than in other soil types (i.e., VCI_1 for CH > VCI_1 for CL, ML, remoldable SM or SC, etc.; based on data from Nuttall et al. 1966; Priddy 1995). Based on the latter observation, they decided to focus on CH soils as the standard for VCI_1 field testing efforts in fine-grained soils and remoldable sands.

The rationale behind the CH standard (which was not instantly defined, but rather evolved over a period of years) included the following:

1. It would not be economically warranted to conduct extensive amounts of VCI_1 testing in all major soil types.
2. Because VCI_1 for CH is the most conservative, using this standard would significantly reduce risk of battlefield immobilization on any soil type.
3. CH soils allow better control and reliability in the testing since the soil strength varies over a much broader range of moisture contents. High plasticity means that the soil has a larger range of moisture over which it behaves plastically, rather than behaving like a hard solid or a liquid material. Control in remoldable sands proved highly difficult.

Ultimately, restricting the data used to develop VCI_1 prediction relationships to CH soils ensures that predictions can be used to both: (a) provide appropriately conservative support for military operations and (b) develop fundamental understanding concerning how vehicle characteristics influence a vehicle's soft-soil mobility. In other words, USACE personnel chose to make CH soil the standard in order to address both of the principal motivators related to battlefield command and control and vehicle acquisition support.

Lane Preparation Conditions

Another key aspect of the test procedures relates to the lane preparation conditions. The original VCI testing was conducted on prepared lanes, wherein researchers dug pits and built prepared lanes constructed to provide somewhat uniform soil strength conditions that could be varied from lane to lane (or test to test in the same lane) (Anon. 1949c). Once predictable trends began to emerge for the influence of vehicle characteristics on VCI performance, they began conducting VCI tests in naturally occurring soil deposits to determine if the trends were still applicable. The results showed that VCI for prepared lanes did not represent VCI performance in natural soils (Anon. 1954a). This observation led them to focus on naturally occurring lanes as the standard for VCI field testing efforts in fine-grained soils and remoldable sands, and it was also one of the key reasons behind the development of the RI soil test method and the RCI soil strength metric.

The rationale behind the natural terrain standard addresses primarily the principal motivator related to battlefield command and control. In operational environments, constructed soil areas (such as roads and dams), which could be compared to the prepared test lanes, are built specifically to prevent soft-soil conditions. Therefore, soft-soil conditions will predominantly occur in naturally occurring soils (such as lakebeds, swamps, and river floodplains).

Soil Profile Layering Conditions

Another key aspect of the test procedures relates to the soil profile layering conditions. The standard VCI test procedure requires cone penetrometer measurements down to a depth of 36 in., which was estimated to exceed the maximum value of the principal depth of influence for soil bearing capacity associated with most military vehicle loadings.

USACE researchers realized that drastic variations (or discontinuities) in soil strength within the principal depth of influence can produce VCI performance measurements that are incompatible with measurements from typical, naturally occurring soft soils where gradual increases in strength or near constant strength with depth are the norm. This realization led them to avoid test lanes with highly abnormal soil strength profiles (e.g., plowed fields) as a standard for VCI field testing in fine-grained soils and remoldable sands. Soil profiles with hard-pan discontinuities are fairly obvious in most situations, but experience and judgment must be applied when deciding whether somewhat abnormal profiles warrant the exclusion of specific lanes.

The rationale behind this standard addresses primarily the principal motivator related to vehicle acquisition support. Using soils with normal strength profiles ensures repeatability and comparability of results.

Critical Layer

Another key aspect of the test procedures relates to the critical layer. The critical layer is the layer of soil that exerts the greatest influence on VCI performance. The standard test procedure for VCI includes a requirement to determine the critical layer for each test series by evaluating the quality of separation in go/no-go test points for various 6-in. (or 12-in.) layers (Kennedy and Rush 1968; Schreiner 1971). USACE researchers developed criteria for estimating what depth range the critical layer is normally located in based on vehicle characteristics (i.e., “normal critical layer”). This guidance on the normal critical layer is provided in Army Field Manual FM 5-430-00-1.

The FM guidance is primarily intended to minimize the number of RI measurements that need to be conducted in military reconnaissance, thereby allowing soldiers to only measure RI in a single layer that is typically critical based on past test results for vehicles similar to the one(s) of interest. However, depending on specific nuances of the soil layering characteristics of the various test lanes used for a VCI test series, a different critical layer can emerge for one test series relative to another for the same type of vehicle (i.e., the critical layer that emerges for a specific test series may not be “normal”).

Therefore, it is important to always consider the soil strengths in various layers when analyzing the results from VCI testing. The normal critical layer should be referred to and given preference in the analysis of VCI measurements, but the key objective is to determine the correct numerical value for the RCI soil strength that actually controlled the performance for the test series and, thereby, ensure consistent and repeatable VCI performance measurements. Experience and judgment must be applied when deciding on the critical layer to apply for VCI measurements.

The rationale behind the normal critical layer criteria provided in the FM relates primarily to the battlefield command and control motivator, whereas the rationale behind the standard critical layer methods used for analysis in VCI testing relates primarily to the vehicle acquisition support motivator.

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Appendix B: The Cone Penetrometer

The instructions provided in this appendix, based largely on TB ENG 37 (1959), apply to the standard cone penetrometer found in the US Army Corps of Engineers trafficability kit. While it is permissible to use alternative cone penetrometers, such as those with digital gages or digital data acquisition systems, all alternative equipment must be validated against standard equipment prior to use.

Components

The cone penetrometer is the principal instrument used in evaluating soils trafficability. The standard 300 psi dial cone penetrometer consists of a 30° cone with 0.5 sq-in. base area, an 18-in.-long rod, which can be joined with other rods to provide an 18- or 36-in. length of rod, a proving ring, a dial gage, and a handle (Figures 14-16). When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. The range of the dial is 0 to 300 psi, and 300 psi is calibrated to a vertical applied force of 150 lb.

The cone penetrometer can also be fitted with a 750 psi dial using a 30° cone of 0.2 sq-in. base area to measure firmer soils.

Standard cone penetrometer rods are marked at 1, 2, 3, 4, 5, 6, 9, 12, 15, 18, 24, 30, 36 in. (from the base of the cone) to indicate the standard penetration depths for cone index readings (Figure 17).

Maintenance

The penetrometer needs little care beyond keeping the instrument free of dirt and rust, keeping all components tight, and frequently checking for zero, and, if necessary, re-zeroing the penetrometer.

If either or both mounting blocks become loose or move, adjust them so that they lie on a diameter of the ring, and then retighten.

The dial gage is a sensitive instrument that should be protected against water and rough usage. Never immerse it in water. Be sure to cushion and secure the dial during transport.

Figure 14. Parts of a cone penetrometer.
1. Handle 2. Mounting block 3. Dial gage
4. Proving ring 5. Dial gage stem
6. Mounting block

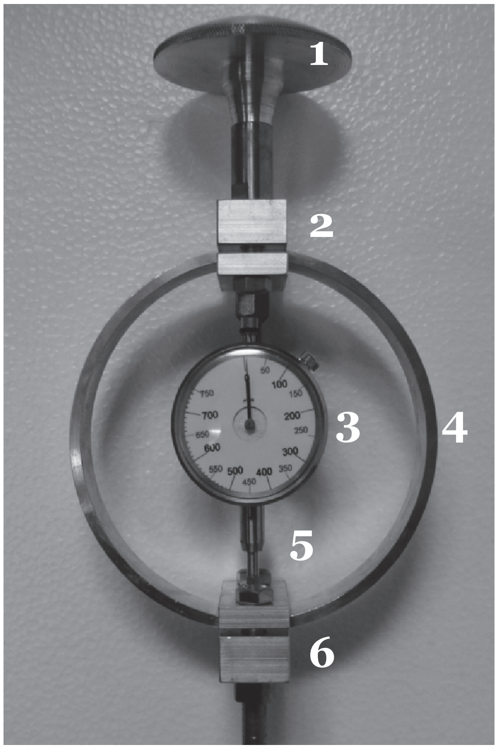


Figure 15. The back of the dial gage.

Figure 16. Parts of a penetrometer. 1. Connection to mounting block 2. Shaft 3. Cone tip

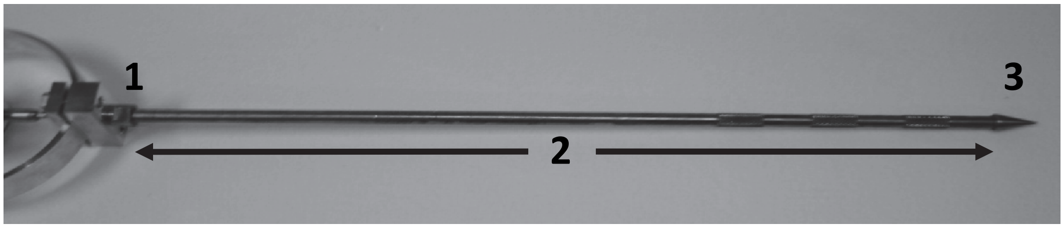
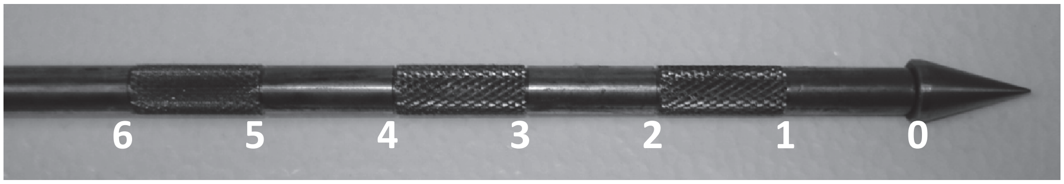


Figure 17. Shaft increments.



Cone tips may become rounded with use. This will not affect the accuracy of the instrument. However, defects in the cone base will affect accuracy. If the base of the cone has excessive wear, the cone should be replaced.

Use

Inspection

Inspect the instrument before using to make sure all nuts, bolts, and joints are tight (Figure 18) and that the dial gage stem contacts the mounting block as shown in Figure 19.

Also check that the base of the cone tip is intact.

Zeroing

Allow the penetrometer to hang vertically from its handle and check that the dial reads “0.” If necessary, loosen the screw (Figure 20) to allow the dial face to rotate, and then rotate the dial face until “0” is under the needle. Finally, retighten the screw.

Re-zero the penetrometer each time that an extension rod is added or removed.

Quickly check the zeroing between measurements, and re-zero as necessary.

Figure 18. Key points for inspection.

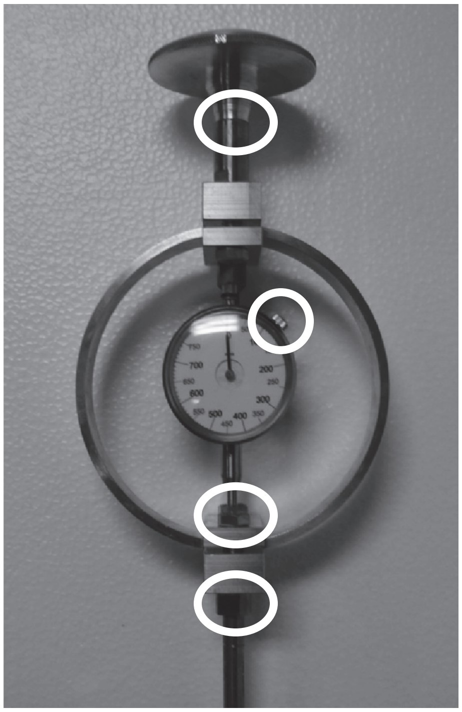


Figure 19. Proper contact between dial gage stem and mounting block.

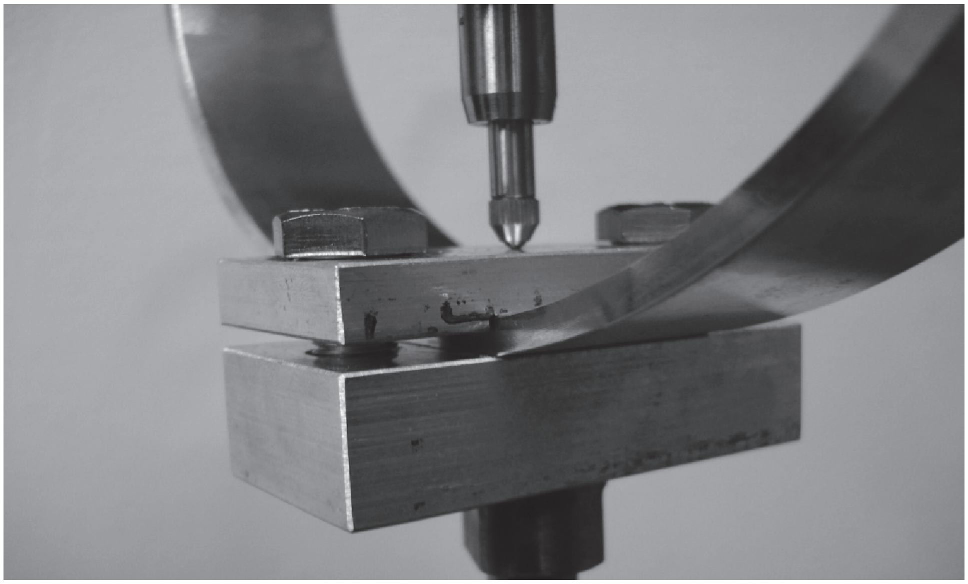
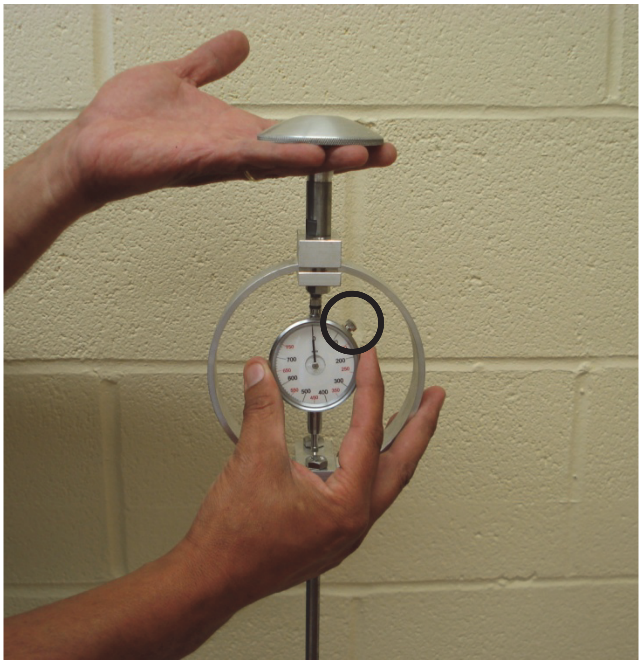


Figure 20. Zeroing the gage.



Operation

Place the hands over each other on the handle, palms down and approximately at right angles as shown in Figures 21 and 22. This will minimize eccentric loading of the proving ring and help keep the rod vertical.

Apply force by pressing the chest against the hands until slow, steady, downward movement occurs (Figure 22). There should be no contact between the operator's hands and the proving ring.

Take a dial reading just as the base of the cone is flush with the ground surface. Continue the slow, steady downward movement (18 in. in approximately 15 seconds or about 1.2 in. per second) and take successive dial readings at 1-in. intervals to a depth of 6 in., at 3-in. intervals to a depth of 18 in., and 6-in. intervals to a depth of 36 in.

At minimum, two people are needed to collect CI readings with the standard equipment. An assistant should be provided to record the readings taken by the operator. The operator will have to shift his vision from the rod at the ground to the dial reading at the proper moment, meanwhile maintaining a constant penetration rate.

Figure 21. Aligning the penetrometer.

Figure 22. Proper use of the penetrometer.

Optionally, CI readings may be performed by a three-person team, with one person pushing the cone and watching for reading increment marks on the shaft, a second person watching the dial and calling out the readings, and a third person recording these readings.

Additional notes

Keep the instrument vertical when taking readings.

Do not attempt to take readings higher than the capacity of the dial. This may over-stress the proving ring.

If the dial capacity is exceeded at a depth of less than the desired reading depth, make another penetration at a nearby location to be assured that the cone is not striking an isolated rock fragment. Note any areas where the dial capacity is exceeded with a 300+ or 750+, based on the dial used.

Never withdraw the instrument by the proving ring. Use the shaft.

Check zero reading after each set of measurements.

Reference

For more information, refer to:

US Department of the Army, 1959. *Soils Trafficability*. TB ENG 37.

Appendix C: Soil Sampling and Remolding

The instructions provided in this appendix, based largely on TB ENG 37 (1959), apply to the remold equipment found in the US Army Corps of Engineers trafficability kit. Any alternative equipment must be validated against standard equipment prior to use.

Soil Sampling

A Hvorslev soil sampler (Figure 23) is used to extract soil samples for remolding tests. This is a piston-type manual soil sampler. One handle is used to lock the piston to prevent loosing the sample (Figure 24). The sampler may also have two checkbars (Figure 24), which can be used to check the sample height.

Use

Force the sampling tube into the soil, being careful to keep the sampler upright. In soft soils, it may be possible to hold one hand on the disk on the top of the sampler while pushing the handle downward with the other hand. In very firm soils two men often are needed to force the sampler into the soil.

Figure 23. Hvorslev soil sampler.

Figure 24. Sampler handle detail:
1. Adjustment screw. 2. Locking handle.
3.Fixed Handle. 4.Short checkbar.
5.Sample checkbar.

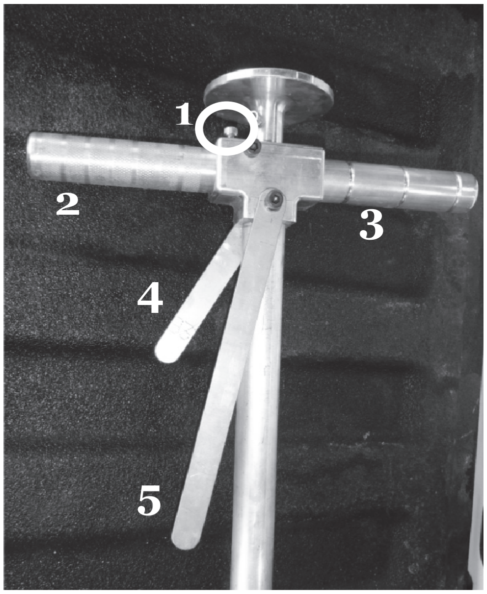


Figure 25. Taking a soil sample.

The sample checkbar may be used to verify that the sampler has extracted an approximately 6 in.-long sample before the sampler is removed from the ground (Figure 26).

Figure 26. Checking proper sample size using the sample checkbar.

After locking the piston rod by turning the handle (Figure 27), twist the instrument slightly and withdraw.

Figure 27. Locking the piston rod to secure sample.

Extrude the sample by unlocking the piston, inverting the sampler, holding the sample tube, and pushing downward on the handle with one foot (Figure 28). If the sample is intended for a remold test, it should be extruded directly into the remold cylinder (Figure 29).

A note on soil density sampling

The short checkbar can be used to extrude a standard-sized sample for simple density measurements. To accomplish this, the sample size should be checked with the sample checkbar first. Then the short checkbar should be extended before extrusion (Figure 30).

Figure 28. Extruding the sample for uses other than remold test.

Figure 29. Extruding the sample into the remold cylinder.

Figure 30. Using short checkbar to extrude density sample.

Then the soil sample should be trimmed with a wire saw (Figure).

Figure 31. Trimming the soil sample.

Using a standard Hvorslev sampler, this process should result in a sample cylinder of 3.453 in. height and 1.8735 in. diameter. These dimensions simplify the density calculation to:

$$\gamma = 0.400 \times M \tag{2}$$

where:

γ = sample density in lb/ft^3, and
M = sample mass in grams.

Before using this calculation, it is necessary to check that the actual sample size is equal to the standard size. Otherwise, the simplified calculation should not be used.

Care

It is essential to keep the inside of the sampling tube reasonably clean. After 5 to 25 samplings (depending upon the soil conditions), clean the sample tube with water and a lubricant, such as WD-40.

If the instrument becomes stiff, remove the tube, disassemble and thoroughly clean the piston. Tube walls and cutting edges are comparatively soft so they should be handled with some care.

Adjustment

The effective piston-rod length should be adjusted to keep the face of the piston flush with the cutting edge of the tube when the piston rod handle (disk) is fully depressed. This is done by loosening the setscrew on the handle, screwing the handle up or down to the correct position, and retightening the setscrew.

Remold Test

Equipment

The remold test kit consists of a Hvorslev sampler, remold cylinder, a drop hammer, and a cone penetrometer (Figure 32). Sample containers and a wire saw (Figure 32) are useful additional equipment for soil sampling, which is often completed immediately after remold testing.

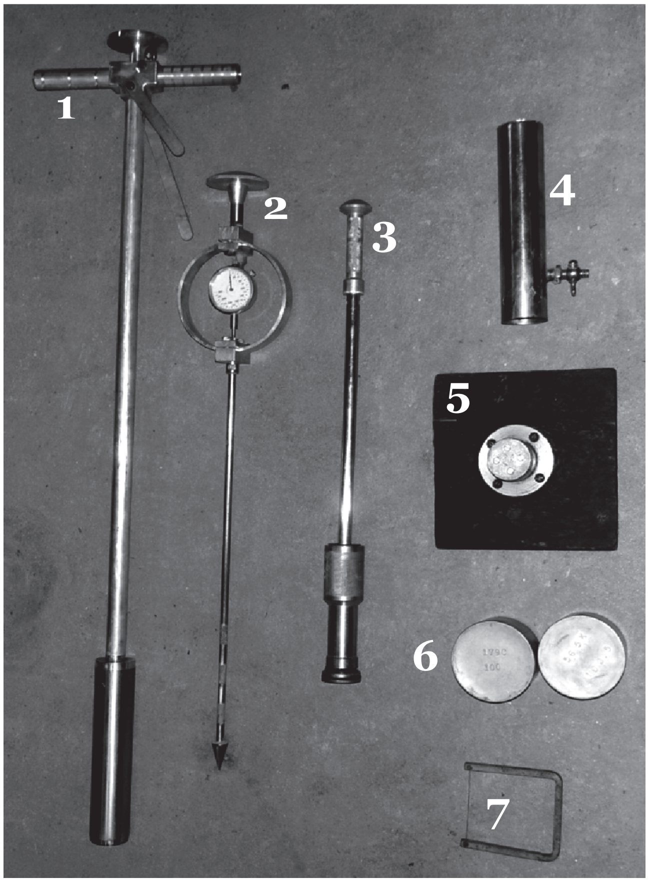
The sampler (described in previous section) is used to obtain the soil sample and place it in the remolding cylinder.

The remold cylinder, a 1.8735 in. inside-diameter, 8 in. long steel cylinder mounted on a base, is used to contain the sample for remolding.

The drop hammer, a 2.5-lb steel hammer sliding on an 18-in. steel staff with handle, is used to apply the necessary remold force.

The penetrometer (described in Appendix A) is used to measure soil strength in the cylinder before and after remolding.

Figure 32. Remold equipment: 1. Hvorslev sampler. 2. Cone penetrometer. 3. Drop hammer. 4. Remold cylinder. 5. Remold cylinder base. 6. Sample containers. 7. Wire saw.



Procedure

Take a sample with the sampler, eject it directly into the remold cylinder (Figure 29), and push it to the bottom of the cylinder with the foot of the drop hammer (Figures 33 and 34).

Measure the strength with the penetrometer (Figure 35) by taking cone index readings as the base of the cone enters the surface of the soil sample and at each successive inch, to a depth of 4 in., for a total of five readings. Occasionally, a sample is so hard that it cannot be penetrated the full 4 in. In such cases the full capacity of the dial (300+ or 750+) is recorded for each inch below the last reading obtained.

Next, apply 100 blows with the drop hammer (Figure 36). Be careful to apply consistent force with each blow by lifting the weight all the way to the top of the shaft and allowing it to freefall to the bottom. Do not throw the weight downward.

Figure 33. Remold sample immediately after extrusion.

Figure 34. Pressing remold sample into place.

Figure 35. Reading cone index.

Figure 36. Remolding the sample with drop hammer.

Measure the cone index as before (five readings beginning with the surface and continuing every inch until 4 in.).

The remold index is computed by dividing the sum of the five CI readings after remolding by the sum of the five CI readings before remolding.

Reference

For more information, refer to:

US Department of the Army, 1959. *Soils Trafficability*. TB ENG 37.

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14. ABSTRACT

This report describes test procedures used to measure the minimum soil strength necessary for a vehicle to consistently complete one pass successfully (one-pass Vehicle Cone Index , VCI_1). The VCI_1 is a vehicle performance metric used to quantify mobility on soft soils. The report scope covers the specific procedures that should be used for evaluations in support of ground vehicle acquisition. The procedures define site selection criteria, test lane layout, soil data collection procedures, and analysis methodology to determine the VCI_1. Rationale behind the test procedures and detailed descriptions of the principal soil strength measurement techniques are provided in supporting appendices.

15. SUBJECT TERMS

Soft soil trafficability	Test procedure	Cone index
Ground vehicle mobility	Soil strength	Remold index
	Rating cone index	

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