Journal of Terramechanics 91 (2020) 185–231

Contents lists available at ScienceDirect

Journal of Terramechanics

journal homepage: www.elsevier.com/locate/jterra

Updated Standards of the International Society for Terrain-Vehicle Systems

Rui He [a,*], Corina Sandu [a], Hoda Mousavi [a], Mohit N. Shenvi [a], Kirsten Braun [b], Ray Kruger [b], P. Schalk Els [b]

[a] *Terramechanics, Multibody, and Vehicle Systems (TMVS) Laboratory, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, United States*
[b] *Vehicle Dynamics Group (VDG), Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria 0002, South Africa*

ARTICLE INFO

Article history:
Received 21 February 2020
Revised 18 June 2020
Accepted 29 June 2020
Available online 30 July 2020

Keywords:
ISTVS standards
Terminology
Soil
Tire
Track
Wheel
Mobility
Test methods
Test equipment

ABSTRACT

The last version of the ISTVS standards was published in the Journal of Terramechanics in 1977. Since then, the document has not been updated, although new concepts, techniques, testing procedures, and technology have been developed in the last 40 years, which renders some content of the 1977 ISTVS standards outdated and in-complete. The ISTVS identified as a priority the need to develop a set of standards for terminology and testing for modern day research on off-road mobility. This paper, for which the work has been funded in part by ISTVS, is an updated version of the 1977 ISTVS standards and covers a range of aspects in off-road mobility for: vehicles, tires, tracks, soil, wheels, modelling approaches, test methods, and equipment.

© 2020 ISTVS. Published by Elsevier Ltd. All rights reserved.

Contents

---

* Corresponding author.
E-mail addresses: herui33@vt.edu (R. He), csandu@vt.edu (C. Sandu), hoda13@vt.edu (H. Mousavi), mshenvi@vt.edu (M.N. Shenvi), Schalk.Els@up.ac.za (P.S. Els).

https://doi.org/10.1016/j.jterra.2020.06.007
0022-4898/© 2020 ISTVS. Published by Elsevier Ltd. All rights reserved.

Nomenclature

ACV	air-cushion vehicle
b	the smaller dimension of the contact patch
b	tire section width
c_a	soil adhesion
C_u	coefficient of uniformity
CBR	California Bearing Ratio
CI	cone index
$\overline{C}\,\overline{I}_z$	average cone index from the soil surface to the soil layer at z penetration depth
CI_0	surface cone index
c	soil cohesion
c_b	soil cohesion (bevameter)
c_c	soil cohesion (Cohron sheargraph)
c_d	soil cohesion (direct shear box)
c_s	soil cohesion (torque tube)
c_t	soil cohesion (triaxial test apparatus)
c_v	soil cohesion (torvane)
d	tire diameter
D	diameter of structural cell
D_{10}	particle diameter corresponding to 10% finer on the particle size distribution curve
D_{50}	average grain size
D_{60}	particle diameter corresponding to 60% finer on the particle size distribution curve
DP	drawbar pull
D_d	relative density
E	Young's modulus
e	void ratio
e_{max}	void ratio, densest state
e_{min}	void ratio, loosest state
F_p	gross tractive effort
F_t	net tractive effort
f_s	external frictional resistance
GEM	ground effect machine
G	shear modulus
G	cone index gradient or penetration resistance gradient
G_s	specific gravity
h	unloaded tire section height
i	slip ratio
j	shear displacement
J_{2D}	second invariant of the deviatoric stress tensor
J_1	first invariant of the stress tensor
K	shear deformation modulus
k	sinkage modulus
k	material parameter of the Drucker-Prager model that can be related to the soil friction angle
k_c	the part of the sinkage modulus influenced by soil cohesion in the Bekker's pressure-sinkage equation
k_{wheel}	wheel mobility number coefficient
k_ϕ	the part of the sinkage modulus influenced by soil friction angle in the Bekker's pressure-sinkage equation
LL	liquid limit
N	wheel numeric
N	number of stems in the structural cell
N_c	clay-tire numeric
N_{cs}	cohesive-frictional soil-tire numeric
N_s	sand-tire numeric
N_{wheel}	wheel mobility number
n	porosity
n	sinkage exponent
p	pressure
PI	plasticity index
PL	plastic limit
PN	power number
q_u	unconfirmed compressive strength
q_{ult}	ultimate bearing capacity
R	rolling resistance (Fig. 1)
RCI	rating cone index
RI	remolding index
r	radius (Fig. 1)
r_R	rolling radius
S	percent saturation
S	skid
s	shear strength (Coulomb's equation)
SEV	surface effect vehicle
SL	shrinkage limit
S_m	stem spacing
$t\ (\Delta t)$	time (an increment of time)
T	torque input
T_w	sticky limit
USCS	Unified Soil Classification System
V	volume, total mass
V_a	volume of air
V_s	volume of solids
V_w	volume of water
VCI	vehicle cone index
v	vehicle speed or forward velocity
W	vehicle weight, gross
W	normal load applied to a tire or wheel (Fig. 1)
W	weight, total mass (the weight of solids and water)
W_s	weight of solids
W_w	weight of water
w_g	gravimetric water content
w_v	volumetric water content
z	sinkage, vertical direction (Fig. 1)
z	penetration depth (of a cone penetrometer)
z_{res}	residual sinkage (rut depth)
α	angle of repose
α	material parameter of Drucker-Prager model that can be related to the soil cohesion
γ_d	dry density, dry bulk density, or bulk density
γ_w	wet density or wet bulk density
γ_{water}	water density
δ	tire deflection
θ_f	entry angle (Fig. 1, Fig. 2)
θ_r	exit angle (Fig. 1, Fig. 2)
μ	coefficient of (external) friction
ν	Poisson's ratio

η	drawbar efficiency
ρ_d	any given dry density
$\rho_{d,\ max}$	maximum dry density
$\rho_{d,\ min}$	minimum dry density
σ	normal stress
$\bar{\sigma}$	effective stress
τ	shear stress
τ_s	shear strength
φ	angle of internal friction
φ_b	angle of internal friction (bevameter)
φ_c	angle of internal friction (Cohron sheargraph)
φ_d	angle of internal friction (direct shear box)
φ_s	angle of internal friction (torque tube)
φ_t	angle of internal friction (triaxial test apparatus)
ω	angular velocity or rotation velocity

1. Introduction

The mission of the ISTVS is to (1) advance the knowledge in terrain-vehicle systems for improvements in engineering practice and for innovation and (2) in the terrain-vehicle domain, to promote the transfer of advanced knowledge to the user for the benefit of society at large in environmental protection, energy conservation, and sustainable development.

Over five decades after its founding in 1962, the ISTVS meets the new challenges of the 21st century through a close-knit international community that has a long history of focused annual conferences, as well as through the Journal of Terramechanics – the leading international journal serving the multidisciplinary global off-road vehicle and soil working machinery industries, and related user community, governmental agencies, and universities.

It is generally agreed that the field of terrain-vehicle (machine) systems is an engineering/applied science discipline. Consequently, it must have a strong focus on practical applications as well as on experimental work. In this context, it is important for the community at large to share common definitions, techniques and methods to enable effective communication at a high technical standard as well as efficient exchange of data sets and models.

As an extensive rework and update of the last version of the ISTVS standards that was published in the Journal of Terramechanics in 1977 (Meyer et al., 1977), this document containes some verbatim material reprinted from Journal of Terramechanics, 1977, Vol. 14, No. 3, International Society for Terrain-Vehicle Systems standards, PP. 153 to 182, Copyright (1977), with permission from the International Society for Terrain-Vehicle Systems. Although denoted as "standards", the last version of the ISTVS standards primarily consisted of: (A) glossary of terrain-vehicle systems; (B) soil-test devices associated with soil-vehicle tests; (C) abbreviations and symbols. The first part was a collection of definitions for commonly used terms related to off-road mobility. The second part included short descriptions of some test equipment. The last part was a list of abbreviations and symbols used in the previous sections. Though their names are not listed as co-authors of this updated standards document, credit must also be given to the authors of the first version of the ISTVS standards: Marvin P. Meyer, I. Robert Ehrlich, David Sloss, Newell R. Murphy, Jr., Robert D. Wismer, and Tibor Czako.

The main difference between this document and the 1977 document are (1) several new terms have been included; (2) outdated terms have been replaced by up-to-date definitions; (3) obsolete references have been replaced with up-to-date ones; (4) more figures have been added; (5) standard measurement methods for soil parameters from other societies and regulatory agencies have been listed; (6) suggestions have been given for standardization of tests with no current standard procedures; (7) suggestions have been given regarding which standard to use when multiple options exist.

Section 2 of the paper presents an alphabetical "Glossary of Terrain-Vehicle Terms". Section 3 describes "Terrain-Test Devices Associated with Terrain-Vehicle Tests". The paper concludes with Section 4 that provides suggestions for "Standard Test Methods". All these sections are based on the 1977 document but were revised and updated with the latest available information. Terms with no asterisk, e.g., "Adhesion, C_a", are the terms from the previous version of the ISTVS standards whose content is kept as it was. Terms marked by one asterisk, e.g., "Amphibious vehicle*", are the terms from the previous version of the ISTVS standards whose content has been updated. Terms marked by two asterisks, e.g., "Angle, entry**", are terms that were not listed on the previous version of the ISTVS standards, but were added into this document. The terms are listed in alphabetical order.

In this document, the American spelling is used, e.g., "tire" not "tyre", "modeling" not "modelling", "behavior" not "behaviour" etc.; the SI units are used, with imperial units occasionally listed in the parentheses that follow.

To improve the usability of the document, a Table of Content has been included at the end of the document, with direct links for all the terms

Comments on the clarity or correctness of a term, new terms that should be added, or any other suggested changes are welcome and are solicited by the Authors. All changes deemed appropriate will be incorporated in the ISTVS standards for its next version. Its next version, after being approved by the ISTVS Board of Directors, will be made available to the community. Comments may be sent to:

Corina Sandu, Ph.D., ASME Fellow, SAE Fellow, Marie Skłodowska-Curie Fellow, Vice-President of ISTVS
Robert E. Hord Jr. Professor and Associate Department Head for Graduate Studies
Director, Terramechanics, Multibody, and Vehicle Systems (TMVS) Laboratory
Mechanical Engineering Department, Virginia Tech, Blacksburg, VA 24061-0710, USA
e-mail: csandu@vt.edu
or
Prof. Schalk Els, Ph.D.
Deputy General Secretary of ISTVS for Europe-Africa
Regional ISTVS Secretary for Africa
Director, Vehicle Dynamics Group (VDG)
Department of Mechanical and Aeronautical Engineering
University of Pretoria, Pretoria 0002, South Africa
e-mail: schalk.els@up.ac.za

2. Glossary of terrain-vehicle terms

2.1. A

2.1.1. Adhesion c_a

In soils, shearing resistance between soil and another material under zero externally applied pressure (ASTM D653-14, 2014).

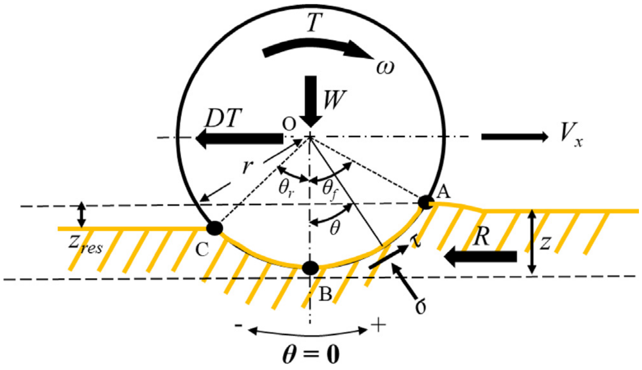


Fig. 1. Schematic of wheel-soil interaction, adapted from (Ishigami, 2008; Wong and Reece, 1967). Note that the schematic here is not a free body diagram about all the forces applied to the wheel or soil.

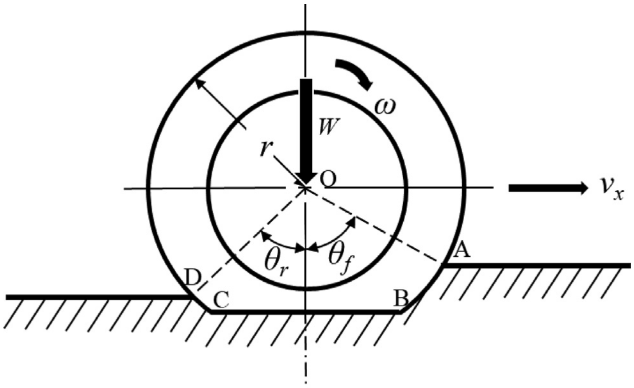


Fig. 2. Schematic of tire-soil interaction, adapted from (Wong, 2008). Note that the schematic here is not a free body diagram about all the forces applied to the tire or soil. This schematic does not represent the tire-soil interaction for all types of soil and tires or portray precisely the real geometry of the tire-soil contact patch; it approximates the real geometry in 2D.

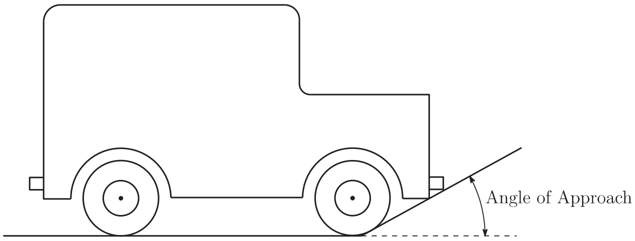


Fig. 3. Schematic of vehicle for angle of approach for a vehicle moving on a rigid, flat ground.

2.1.2. Air-cushion vehicle, ACV (ground effect machine, hovercraft, surface effect vehicle)

A vehicle that rides on a layer of air generated by its own fans and trapped underneath by contoured skirts. Such vehicles need no direct contact with the surface (Quick, 1973).

2.1.3. Amphibious vehicle*

A wheeled or tracked vehicle capable of operating on both land and water [Quick, 1973; Office of the Chairman of the Joint Chiefs of Staff, 2019].

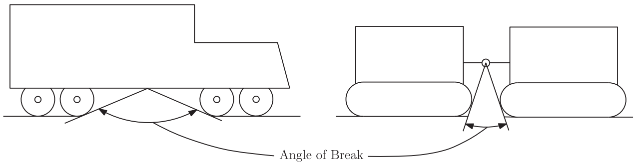


Fig. 4. Schematic of vehicle for angle of break.

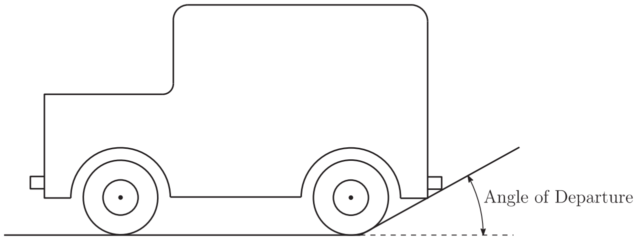


Fig. 5. Schematic of vehicle for angle of departure for a vehicle moving on a rigid, flat ground.

2.1.4. Angle, entry, θ_f**

The angle from the vertical line, normal to the direction of travel, to the line connecting the wheel or tire center and the foremost contact point between the wheel or tire and the soil, as shown by Figs. 1 and 2.

2.1.5. Angle, exit, θ_r**

The angle from the vertical line, normal to the direction of travel, to the line connecting the wheel or tire center and the rearmost contact point between the wheel or tire and the soil, as shown by Figs. 1 and 2.

2.1.6. Angle of approach, vehicle*

The maximum angle, equal to or less than 90°, that can be formed by the intersection of the vehicle contact plane and a plane tangent to the forward part of the foremost traction or transport elements and touching the foremost part of the vehicle body (Fig. 3). In the case of a vehicle moving on a soil, no plane is tangent to the forward part of the foremost traction or transport elements, the angle of approach is the angle formed by the intersection of the vehicle-soil contact plane and a plane touching the foremost part of the traction or transport element-soil contact area and the foremost part of the vehicle body.

2.1.7. Angle of break, vehicle

The maximum angle that can be formed beneath a wheeled vehicle by the intersection of two planes touching any two adjacent traction elements with the apex touching the vehicle (Fig. 4).

2.1.8. Angle of departure, vehicle*

The maximum angle, equal to or less than 90°, that can be formed by the intersection of the vehicle contact plane and a plane tangent to the rearward part of the rearmost traction or transport elements and touching the rearmost part of the vehicle body (Fig. 5). In the case of a vehicle moving on a soil, no plane is tangent to the rearward part of the rearmost traction or transport elements, the angle of approach is the angle formed by the intersection of the vehicle-soil contact plane and a plane touching the rearmost part of the rearmost traction or transport element-soil contact area and the rearmost part of the vehicle body.

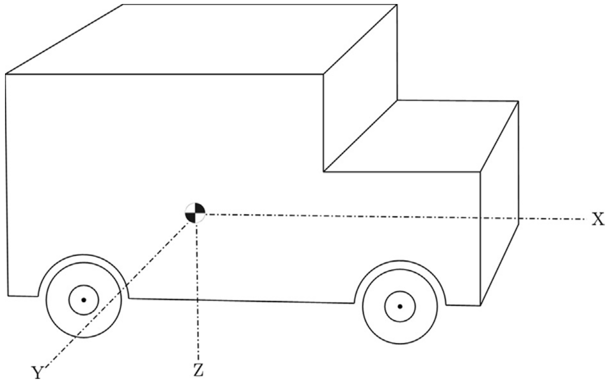


Fig. 6. Vehicle axis system. The origin of the XYZ axes is at the center of gravity of the vehicle. X-axis points forward, Y-axis points right, and Z-axis points downward.

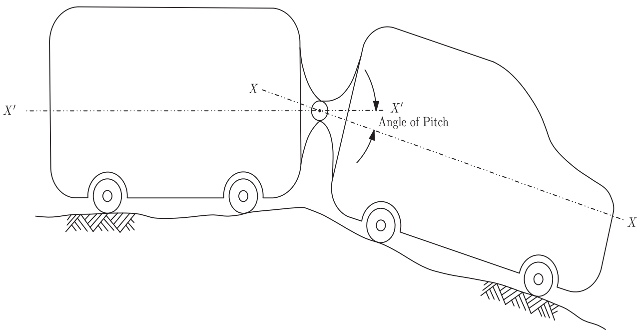


Fig. 7. Schematic of vehicle for angle of pitch.

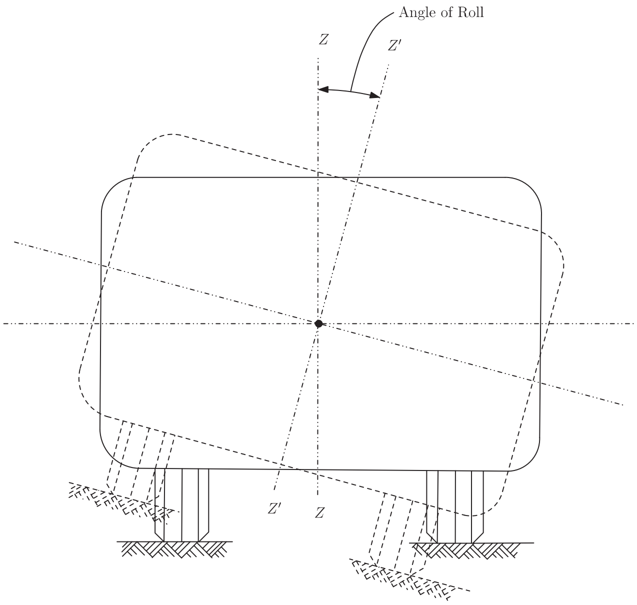


Fig. 8. Schematic of vehicle for angle of roll.

2.1.9. Angle of internal friction (soil friction angle or angle of shear resistance), φ^*

Angle between the axis of normal stress and the tangent to the Mohr envelope at a point representing a given failure-stress condition for a soil; the Mohr envelope expresses the relationship between shear stress and normal stress acting within the soil (ASTM D653-14, 2014).

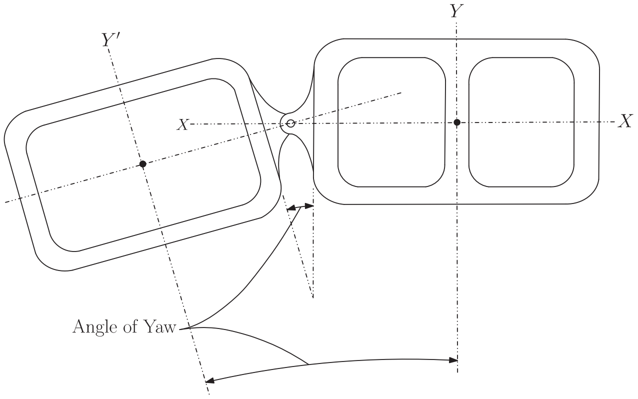


Fig. 9. Schematic of vehicle for angle of yaw.

2.1.10. Angle of pitch (pitch)

This angle pertains to the X-Z plane (Fig. 6). For multi-unit vehicles, this is the angle between the X-axes of adjacent units (Fig. 7; Wismer, 1965).

2.1.11. Angle of repose, α

Angle between the horizontal and the maximum slope of its surface that a soil assumes through natural processes (ASTM D653-14, 2014).

2.1.12. Angle of roll (roll)

This angle pertains to relative movements in the Y-Z plane (Fig. 6). For multi-unit vehicles, this is the angle between the Z-axes of adjacent units (Fig. 8; Wismer, 1965).

2.1.13. Angle of shear resistance**

See angle of internal friction.

2.1.14. Angle of yaw (yaw)

This angle pertains to relative movements in the X-Y plane (Fig. 6). For multi-unit vehicles, this is the angle between the Y-axes of adjacent units (Fig. 9; Wismer, 1965).

2.1.15. Artifact**

Piece of human-manufactured material; a constituent of mineral soil (Soil Science Division Staff, 2017).

2.1.16. Atterberg limits*

In cohesive soils, originally, six "limits of consistency" of fine-grained soils were defined by Albert Atterberg: the upper limit of viscous flow, the liquid limit, the sticky limit, the cohesion limit, the plastic limit, and the shrinkage limit. In current engineering usage, the term usually refers only to the moisture content limits used for separating the solid, semisolid, plastic, and semiliquid phases of soil which are the shrinkage limit, the plastic limit, and the liquid limit respectively (ASTM D653-14, 2014).

For the standard measurement methods of shrinkage limit, see (ASTM D4943-18, 2018; US Army Corps of Engineers, 1970).

For the standard measurement methods of plastic limit and liquid limit, see (ASTM D4318–17, 2017; US Army Corps of Engineers, 1970; ISO 17892-12:2018, 2018).

2.2. B

2.2.1. Bearing capacity

See ultimate bearing capacity.

2.2.2. Bearing capacity, ultimate (bearing capacity), q_{ult}

The average load per unit of area required to produce failure by rupture of a supporting soil mass (ASTM D653-14, 2014).

2.2.3. Bekker-Wong terrain parameters**

These parameters for various types of terrain are obtained using the Bevameter and are for analyzing various aspects of vehicle-terrain interaction (Huang et al., 2020):

(a) Pressure-sinkage parameters;
(b) Internal terrain shear parameters;
(c) Vehicle running gear surface-terrain shear parameters (e.g., rubber-terrain shear parameters for evaluating the traction of rubber tires, rubber tracks, or tracks with rubber pads);
(d) Vehicle belly material-terrain shear parameters (for evaluating vehicle belly-terrain interaction and associated drag);
(e) Parameters for characterizing the response of terrain to repetitive normal and shear loadings.

2.2.4. Bellying

The condition that exists when vehicle sinkage is so great that the under-carriage of the vehicle is in contact with the ground (Tripartite Working Group on Ground Mobility, 1961).

2.2.5. Bellying out

The condition of bellying when the vehicle is immobilized.

2.2.6. Bevameter test**

The test includes two basic parts in its original form: (1) the pressure-sinkage test, with at least two sizes of plates to obtain terrain pressure-sinkage parameters; (2) the shear test, using an annular shear ring under various normal loads to obtain internal terrain shearing characteristics (Bekker, 1969). It has later been expanded to include rubber-terrain shear test, vehicle belly material-terrain shear test, and response to repetitive normal and shear loading test (see Bekker-Wong terrain parameters).

2.2.7. Bogie

A suspension assembly consisting of tandem axles, interconnected by walking beams which pivot vertically about a cross member (trunnion axle). Also, a tandem axle assembly without a distinct walking beam but interconnected by a system of crank and links in such a manner that when an axle experiences a vertical force or displacement a corresponding change in load or position is reflected in the other axle (U.S. Army Material Command, 1965).

2.2.8. Braking mode**

The mode in which the axle torque input (the driving torque) is small enough or zero or braking torque is positive so that the vehicle or traction element is moving at negative slip (Tai and Tomizuka, 2000) or at negative net tractive effort (Muro and O'Brien, 2004). In (Kutzbach et al., 2019), braking mode is defined to be a mode in which the braking torque is positive, and the net tractive effort is negative; the mode, in which the driving torque is positive and small, and the net tractive effort is negative, is defined to be neutral mode.

2.2.9. Branching height*

Distance from the soil surface to the lowest branch (for the plants with only stems yet no trunk) or stem (for the plants with a trunk and stems, e.g., a tree) (Wismer, 1965).

2.2.10. Buoyancy

The weight of the displaced volume of the medium in which, or on which, the vehicle is operating.

2.2.11. Buoyancy reserve

Excess buoyancy above that required for the vehicle to float.

2.2.12. Bulk density*

Same as dry density.

2.2.13. Bulk density, dry**

Same as dry density.

2.2.14. Bulk density, wet**

Same as wet density

2.2.15. Bulldozing**

Movement of a soil mass by a vehicle, traction element, or a bulldozer blade in a parallel and forward direction.

2.2.16. Bulldozing resistance**

The soil resistance exerted on a bulldozing tool from the horizontal soil deformation.

2.3. C

2.3.1. California Bearing Ratio (CBR)*

The ratio of (1) the force per unit area (stress) on the piston required to penetrate 2.54 mm (0.1 in.) or 5.08 mm (0.2 in.) of a soil mass to (2) the stress required to penetrate a standard material of well-graded crushed stone (ASTM D653-14, 2014; ASTM D1883-16, 2016). (See Section 3 for description of test equipment.).

For the standard measurement methods of CBR, see (ASTM D1883-16, 2016; ASTM D6951/D6951M–18, 2018).

2.3.2. Camber angle**

The angle between the Z_T-axis (Fig. 10) and the wheel plane (Society of Automotive Engineers, 2008).

2.3.3. Clump spacing, plant*

The distance from the center of a selected clump of plants, with stems of 25 mm diameter or larger, to the center of the nearest neighbor clump in a randomly distributed population of clumps (USAE Waterways Experiment Station, 1963).

2.3.4. Clumps, plant

A number of similar individual plants closely collected together forming a mass in which the crowns are intermingled (Mills and Clagg, 1964).

2.3.5. Cluster, plant

A number of similar individual plants collected together forming a contiguous group which visually appears to be coherent relative to the distribution of other similar individuals (Mills and Clagg, 1964).

2.3.6. Coarse fragment**

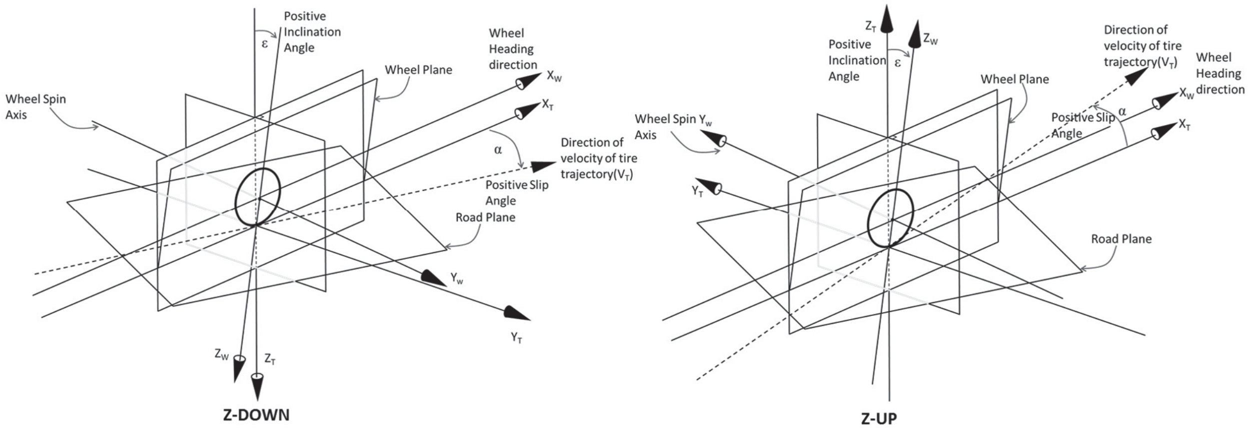
Particles of mineral soil larger than or equal to 2 mm in diameter (Jahn et al., 2006); consists of rock fragments, pararock fragments, and discrete artifacts (Soil Science Division Staff, 2017).

2.3.7. Coarse-grained snow

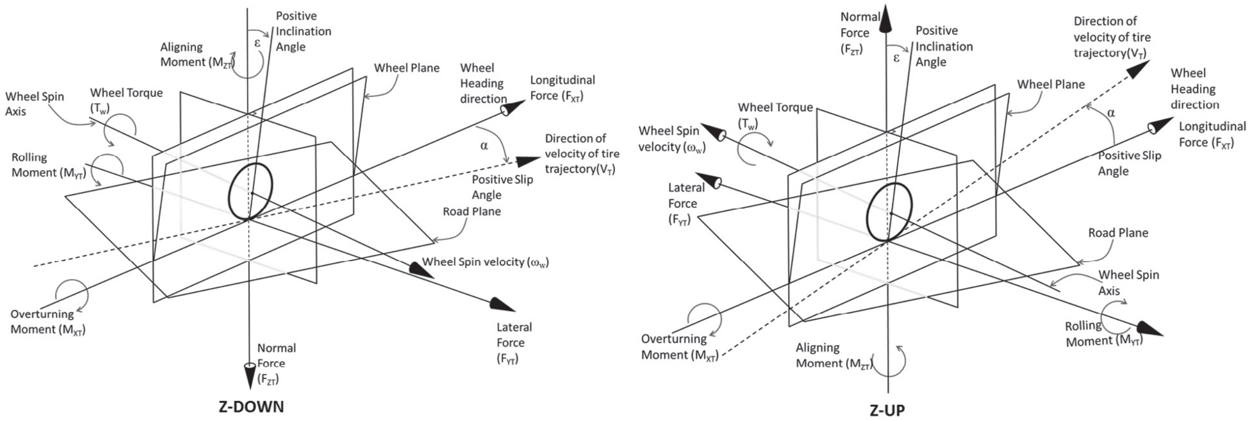
Snow crystals having a mean diameter larger than 2 mm (U.S. Army Engineer Waterways Experiment Station, 1960).

2.3.8. Coarse-grained soil*

A soil containing 50% or less material smaller in diameter than 0.075 mm (No. 200 US standard sieve) (ASTM D2487-17, 2017).



(a) Tire axes.



(b) Tire forces and moments.

Fig. 10. Tire axis system (Society of Automotive Engineers, 2008), adapted from (Society of Automotive Engineers, 2008).

2.3.9. Coefficient of (external) friction, μ^*

In the context of off-road mobility and terramechanics study, this is the ratio between the shearing resistance due to friction and the normal stress acting on the contact area between the soil (or surface material of soil, e.g., ice) and another material, normally the material of traction element (Society of Automotive Engineers, 1967a).

2.3.10. Coefficient of internal friction**

The tangent of the angle of internal friction, tanφ in the Coulomb's equation (ASTM D653-14, 2014).

2.3.11. Coefficient of uniformity, C_u*

The ratio D_{60}/D_{10}, where D_{60} is the particle diameter corresponding to 60% finer on the particle size distribution curve, and D_{10} is the particle diameter corresponding to 10% finer on the particle size distribution curve (ASTM D653-14, 2014). The coefficient of uniformity can be found on the particle size distribution curve (see particle size distribution).

2.3.12. Cohesion, c

The portion of the shear strength of a soil indicated by the term c, in Coulomb's equation (ASTM D653-14, 2014).

2.3.13. Cohesionless soil*

A soil that has shear strength due primarily to internal friction and has negligible cohesion. If this soil is unconfined, it has little or no strength when air-dried and has little or no cohesion when submerged (ASTM D653-14, 2014).

2.3.14. Cohesive soil*

A soil that has shear strength due primarily to cohesion and negligible internal friction. If this soil is unconfined, it has considerable strength when air-dried and has significant cohesion when submerged (ASTM D653-14, 2014).

2.3.15. Cohesive-frictional soil

A soil that has shear strength attributable both to cohesion and to internal friction.

2.3.16. Compaction*

The densification of soil by means of mechanical manipulation which results in the reduction of air voids in the soil. Also, the state of compaction is sometimes referred to as compaction.

The soil parameters commonly used to characterize soil compaction (the state of soil compaction) are bulk density and relative compaction. There are also other soil parameters that were used to characterize soil compaction, e.g., cone index gradient, the same as the penetration resistance gradient (Naranjo et al., 2014); compaction depth, defined as the shallowest depth at which the difference between bulk densities of trafficked and non-trafficked soil was less than 0.05 Mg/m^3 (Adam and Erbach, 1995); degree of compactness, defined as the bulk density of a soil in percent of a reference dry bulk density of the same soil obtained by a standardized, long-term uniaxial compression test at a stress of 200 kPa (Håkansson and Lipiec, 2000).

2.3.17. Compaction, percent**

Same as compaction, relative.

2.3.18. Compaction, relative (percent compaction)**

The ratio, expressed as a percentage, of soil bulk density to the maximum soil bulk density determined from a standard compaction test (ASTM D653-14, 2014).

2.3.19. Compaction curve**

Or Proctor curve, the curve that shows the variation in the dry density or dry unit weight with the gravimetric water content for a test soil (ASTM D653-14, 2014); the curve can be obtained by conducting the compaction test.

2.3.20. Compaction resistance**

The soil resistance to compacting the soil, opposite to the direction of travel, exerted on a traction or transport element

2.3.21. Compaction test**

A test in which the soil samples of one soil are compacted at various levels of soil compaction to determine the maximum dry density or dry unit weight or to obtain the curve of dry density or dry unit weight versus gravimetric water content (ASTM D653-14, 2014).

For the standard test methods of compaction test, see (ASTM D698-12e2, 2012).

2.3.22. Cone index (cone penetration resistance or cone resistance), CI*

The force per unit base area required to push a cone penetrometer (see Section 3 for the description of cone penetrometer) through the soil (Knight and Freitag, 1962; ASAE S313.3 FEB1999 (R2018), 2018; ASAE EP542 FEB1999 (R2018), 2018). ASTM emphasized that the cone index only represents the end-bearing component of penetration resistance (ASTM D3441-16, 2016). ASABE states that the surface cone index reading, at zero penetration depth, is measured at the instant the base of the cone is flush with the soil surface (ASAE EP542 FEB1999 (R2018), 2018). Also, ASABE claims that, in the mobility or trafficability study, the average cone index for the top 150 mm of soil depth is used (ASAE EP542 FEB1999 (R2018), 2018).

For the standard measurement methods of cone index using a cone penetrometer, see (ASAE EP542 FEB1999 (R2018), 2018 and ASTM D3441-16, 2016).

2.3.23. Cone index gradient (penetration resistance gradient), G*

Cone index gradient can be found on the plot of variation in cone index with penetration depth and is defined as (Rula and Nuttall, 1971):

$$G = \frac{\overline{CI}_z - CI_0}{z/2} \tag{1}$$

where G is cone index gradient, z is penetration depth, $\overline{CI}_z$ is average cone index from the soil surface to the soil layer at z penetration depth, and CI_0 is surface cone index.

Note that regarding the criterion as to the measurement of CI_0, ASABE states that the surface cone index reading is measured at the instant the base of the cone is flush with the soil surface (ASAE EP542 FEB1999 (R2018), 2018)

2.3.24. Cone resistance**

Same as cone index

2.3.25. Consistency

The relative ease with which a soil can be deformed (ASTM D653-14, 2014).

2.3.26. Consolidation

The gradual reduction in volume of a soil mass resulting from an increase in compressive stress (ASTM D653-14, 2014).

2.3.27. Contact area (contact patch or contact surface)**

The portion of a traction element or transport element in contact with the supporting surface. In some literature, e.g., the ASABE standard (ANSI/ASAE S296.5 DEC2003 (R2018), 2018), contact area is the projection of the aforementioned portion onto a plane parallel to the undisturbed supporting surface.

2.3.28. Coulomb's equation (Mohr-Coulomb failure criterion or Mohr-Coulomb model)*

In two dimensions, for an isotropic soil, the failure happens when the shear stress reaches the value of shear strength that satisfies a linear relationship between the shear strength, s or τ_s, of soil and the pressure, p, or the normal stress, σ, on an internal surface. The linear relationship (the Mohr-Coulomb model) is written as:

$$s = c + p\tan\varphi \tag{2}$$

or as

$$\tau_s = c + \sigma\tan\varphi \tag{3}$$

where c is cohesion, and φ is angle of internal friction (Contreras et al., 2013; ASTM D653-14, 2014).

2.3.29. Critical layer*

The soil layer which is considered most significant in terms of trafficability. Its depth varies with the weight and type of vehicle and traction element and soil profile.

2.3.30. Cruising range

The total mileage a vehicle can operate on the usable fuel in its tanks (U.S. Army Transportation Combat Developments Agency, 1962). Note: this is a function of surface condition, mission, payload, and other factors.

2.3.31. Cross-country terrain

Terrain not specifically improved for vehicular traffic (U.S. Department of Defense, 1968).

2.4. D

2.4.1. Damping**

Reduction in the amplitude of vibration of a body or system due to dissipation of energy internally or by radiation (ASTM D653-14, 2014).

2.4.2. Damping coefficient (damping rate)**

For a vibrating system with viscous damping, the ratio of the magnitude of a force that resists an element in the vibrating system to the magnitude of the element velocity; that force is in a direction opposite to the element velocity and leads to the energy dissipation.

2.4.3. Damping coefficient, critical**

The minimum viscous damping coefficient that will allow a displaced system to return to its initial position without oscillation (ASTM D653-14, 2014).

2.4.4. Damping ratio**

For a vibrating system with viscous damping, the ratio of actual damping coefficient to the critical damping coefficient (ASTM D653-14, 2014).

2.4.5. Drawbar coefficient*

The ratio of drawbar pull to gross vehicle weight. If applied to a traction element, e.g., a tire, the drawbar pull coefficient is the same as net tractive effort coefficient (coefficient of traction).

2.4.6. Drawbar efficiency, η (tractive efficiency)*

The product of drawbar pull and vehicle speed (if applied to a traction element, the traction element speed) in the direction of travel divided by power input to the traction elements. It is defined by the equation:

$$\eta = \frac{DPv}{T\omega} \tag{4}$$

where η is drawbar efficiency, DP is drawbar pull, v is vehicle speed, T is torque input to the traction elements, and ω is rotation velocity of the torque input shaft.

2.4.7. Drawbar power (vehicle output power)*

The product of drawbar pull and vehicle speed (if applied to a traction element, the traction element speed) in the direction of travel (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.4.8. Drawbar pull, DP (pull)*

The force, produced by the vehicle at the drawbar or hitch, available for external work, in a direction parallel to the horizontal surface over which the vehicle is moving (ANSI/ASAE S296.5 DEC2003 (R2018), 2018). Speaking of drawbar pull for a traction element, e.g., a tire, the drawbar pull is the same as the net tractive effort.

2.4.9. Drawbar pull-slip curve

A plot of the drawbar pull versus slip for a given vehicle in a given soil condition (Tripartite Working Group on Ground Mobility, 1961).

2.4.10. Driving mode (traction mode)**

The mode in which the axle torque input is large enough so that the vehicle or traction element is moving at positive slip (Tai and Tomizuka, 2000) or at positive net tractive effort (Muro and O'Brien, 2004).

2.4.11. Drucker-Prager model (Drucker-Prager failure criterion)**

A pressure-dependent model to describe the plastic deformation of soils and a smooth generalization of Mohr-Coulomb failure criterion that includes the effects of all the principal stresses on soil shearing resistance (Wulfsohn and Adams, 2002). The Drucker-Prager model can be expressed as:

$$\sqrt{J_{2D}} - \alpha J_1 - k = 0 \tag{5}$$

where J_{2D} is the second invariant of the deviatoric stress tensor, J_1 is the first invariant of the stress tensor, and α and k are the material parameters that can be related to the soil cohesion and friction angle, respectively.

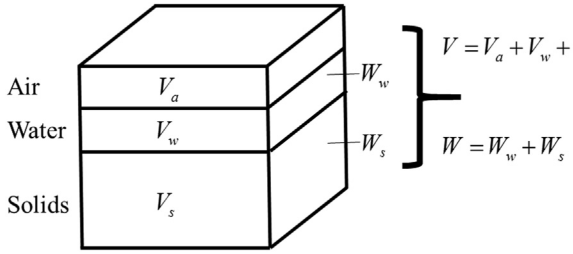


Fig. 11. Unit volume of soil divided into its components.

2.4.12. Dry density (bulk density or dry bulk density), γ_d*

The weight of soil solids, W_s, per unit of total volume of soil mass, V; that is

$$\gamma_d = W_s/V \tag{6}$$

where γ_d is dry density (Fig. 11; ASTM D653-14, 2014).

For the standard measurement methods of dry bulk density, see (ASTM D7263-09(2018)e2, 2018; ASTM D2167-15, 2015; ASTM D1556/D1556M-15e1, 2015; ASTM D2937-17e2, 2017; ASTM D4914/D4914M-16, 2016; ASTM D5030/D5030M−13a, 2013; ASTM D7698-19, 2019; ASTM D6780/D6780M-19, 2019; ASTM D6938-17a, 2017; ASTM D7830/D7830M-14, 2014; ISO 11272:2017, 2017; ISO 17892-2:2014, 2014).

2.4.13. Dry unit weight**

Dry density multiplied by standard acceleration of gravity (ASTM D653-14, 2014).

2.5. E

2.5.1. Effective stress (effective pressure or intergranular pressure), $\bar{\sigma}$*

The average normal force per unit area transmitted from grain to grain of a soil mass. It is the stress that is effective in mobilizing internal friction (ASTM D653-14, 2014).

2.5.2. Elasticity**

The property of a material that returns to its original form or condition after the applied force is removed (ASTM D653-14, 2014).

2.5.3. Embedding**

An anomalous situation experienced by a vehicle after near 100%-wheel slip and high sinkage, the vehicle is still able to make progress in at least one direction by using various maneuvers of the free wheels (Gonzalez and Iagnemma, 2018).

2.5.4. Entrapment**

A critical situation experienced by a vehicle after 100%-wheel slip, there is no possibility to make progress in any direction and the mobility capability of the mission ends (Gonzalez and Iagnemma, 2018).

2.5.5. Environmental effect

A measurable or otherwise definable effect imposed by a specific environmental factor, or by a combination of such factors.

2.5.6. Environmental factor

A specific attribute of the environment that can be described adequately in quantitative terms, e.g. temperature.

2.5.7. Environmental factor class

A specific range of values for an environmental factor.

2.5.8. Exiting performance

The ability of a vehicle to exit unaided from a specified hydrologic geometry feature.

2.5.9. External frictional resistance, f_s

The portion of shearing resistance between soil and another material which is proportional to the normal stress (Society of Automotive Engineers, 1967a).

2.6. F

2.6.1. Field-maximum moisture content

The naturally recurring average highest moisture content of a soil layer in its natural position.

2.6.2. Field-minimum moisture content

The naturally recurring average lowest moisture content of a soil layer in its natural position.

2.6.3. Fine earth**

Particles of mineral soil smaller than 2 mm in diameter (Soil Science Division Staff, 2017).

2.6.4. Fine-grained snow

Snow crystals having a mean diameter of 2 mm or less (U.S. Army Engineer Waterways Experiment Station, 1960).

2.6.5. Fine-grained soil*

A soil containing more than 50% material smaller in diameter than 0.075 mm (No. 200 U.S. standard sieve) (ASTM D2487-17, 2017).

2.6.6. Floating capability

The inherent buoyancy of a vehicle.

2.6.7. Flotation

(1) For water–same as buoyancy. (2) For ground–The ability of a tire or vehicle to resist sinkage in soft terrain.

2.6.8. Fording depth

The depth of water that a vehicle can negotiate under its own power. (Fording depth is unlimited for vehicles that can swim.) (U.S. Army Transportation Combat Developments Agency, 1962).

2.6.9. Freeboard

The distance from the waterline to the lowest point on the rim of a static floating vehicle in still water (Fig. 12).

2.6.10. Free roll (free rolling)**

A type of motion in which a wheel or tire is rolling at zero driving torque and braking torque (Muro and O'Brien, 2004; Wong, 2008). Alternatively, free roll is defined to be a type of motion in which a wheel or tire is rolling under self-propelled condition, i.e., zero net tractive effort (drawbar pull) (Zoz and Grisso, 2003; Kutzbach et al., 2019).

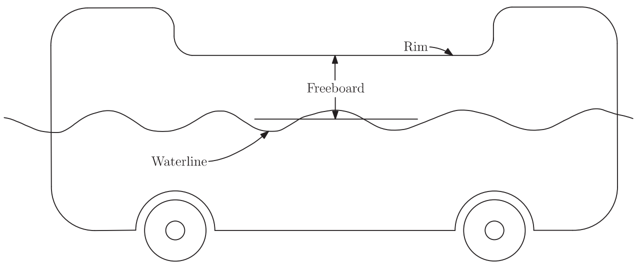


Fig. 12. Schematic of vehicle wading through water.

2.7. G

2.7.1. Gradation**

Same as particle size distribution.

2.7.2. Grade

Same as slope.

2.7.3. Gradeability

The maximum grade (expressed in percent or degrees) that a fully loaded and equipped vehicle can climb at a constant speed on a smooth concrete course when operating in a specified gear (U.S. Army Transportation Combat Developments Agency, 1962).

2.7.4. Grain size, average**

The diameter of the soil particles that have a percentage finer by weight of 50% (Muro and O'Brien, 2004) and denoted by D_{50}. The average grain size can be found on the particle size distribution curve (see particle size distribution).

2.7.5. Ground clearance

The vertical distance from the contact plane of a vehicle to the lowest point on the vehicle's undercarriage or hull.

2.7.6. Ground effect machine, GEM

Same as air-cushion vehicle.

2.7.7. Ground pressure (contact pressure)**

The actual pressure exerted vertically on the ground surface (e.g., soil surface or non-deforming surface) by the traction and transport elements of a vehicle (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.7.8. Ground pressure, nominal (average ground pressure)**

The load of a vehicle, traction element, or transport element, normal to the undisturbed supporting surface, divided by total contract areas (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.7.9. Grouser (track cleat, track grouser)*

A projection on a traction element intended to improve or develop traction (see track shoe for an example). Generally, "lug" is associated with rubber traction element such as tires and rubber tracks, while "grouser" is associated with steel traction element such as wheels and steel tracks (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.7.10. Grouser face

The outermost surface of the grouser.

2.8. H

2.8.1. Hang up

Contact between one or more obstacles and the undercarriage of a vehicle that causes immobilization.

2.8.2. Heave

Linear motion of a vehicle parallel to the Z-axis (Fig. 6).

2.8.3. Highway performance

Those characteristics pertaining to vehicle operations on improved roads.

2.8.4. Hovercraft

Same as air-cushion vehicle.

2.8.5. Humus**

A brown or black material that is the organic portion of soil formed by the partial decomposition of vegetable or animal matter (ASTM D653-14, 2014). Alternatively, in (Jahn et al., 2006), humus is defined as the well-decomposed organic matter.

2.8.6. Hydrologic geometry feature

A channel, stream, pond, lake, or other depression that contains water. When dry, the configuration is not considered a hydrologic geometry feature (see lake, river, stream).

2.8.7. Hysteresis**

The fact that in the loading–unloading cycle, the stress at certain strain in loading differs from the stress at the same strain in unloading due to the energy dissipation in the cycle. In the context of off-road mobility and terramechanics study, hysteresis has been observed in tires and on organic terrain (Wong, 2008): in tires, the hysteresis causes the non-symmetrical normal stress distribution along the tire contact patch and hence results in internal rolling resistance; on organic terrain, the pressure at certain sinkage in unloading differs from that at the same sinkage in reloading.

2.9. I

2.9.1. Immobilization

The condition that exists when a vehicle can no longer propel itself.

2.9.2. Internal friction**

The portion of the shear strength of a soil or rock indicated by the terms $p\cdot\tan\varphi$ in the Coulomb's equation. It is usually considered to be due to the interlocking of the soil or rock grains and the resistance to sliding between the grains (ASTM D653-14, 2014).

2.10. J

2.10.1. Jounce*

The relative displacement of the sprung and unsprung masses in a suspension system in which the distance between the masses decreases (Fig. 13).

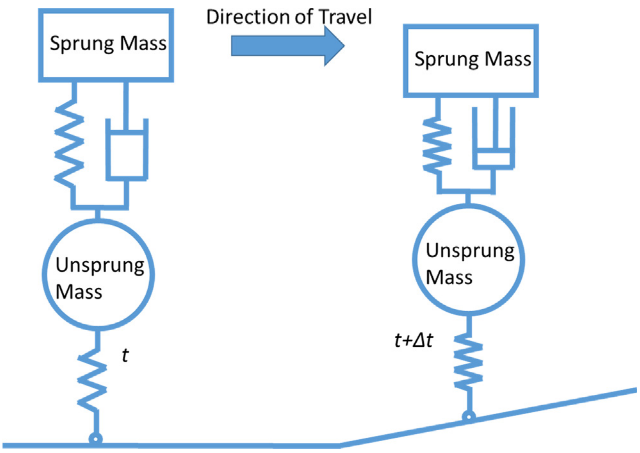


Fig. 13. Schematic illustrating jounce.

2.11. L

2.11.1. Lake

A hydrologic geometry feature that confines water.

2.11.2. Landscape type

A region throughout which a specific assemblage of environmental factor classes occurs, and throughout which those factor classes are related to each other in a similar way (U.S. Department of Defense, 1968).

2.11.3. Liquid limit, LL*

In cohesive soils, the Atterberg limit (the water content, in percent) separating the plastic and semi-liquid phases of soil; the boundary between the plastic and semi-liquid phases is arbitrarily defined (ASTM D653-14, 2014).

For measurement methods of liquid limit, see Atterberg limits.

2.11.4. Load, dynamic**

The total force normal to the undisturbed supporting surface on which the vehicle, traction element, or transport element is operating; the dynamic load is the sum of the static load and any additional forces such as load transfer (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.5. Load, static**

The total force normal to the supporting surface on which the vehicle, traction element, or transport element is standing with zero input torque (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.6. Load carrying index

The product of payload weight, and vehicle speed divided by the installed power of the vehicle (Tripartite Working Group on Ground Mobility, 1961).

2.11.7. Load transfer (weight transfer)**

See weight transfer.

2.11.8. Lug*

Any extended parts on the traction element (tire or track) intended to improve traction or propulsion. Generally, "lug" is associated with rubber traction element such as tires and rubber

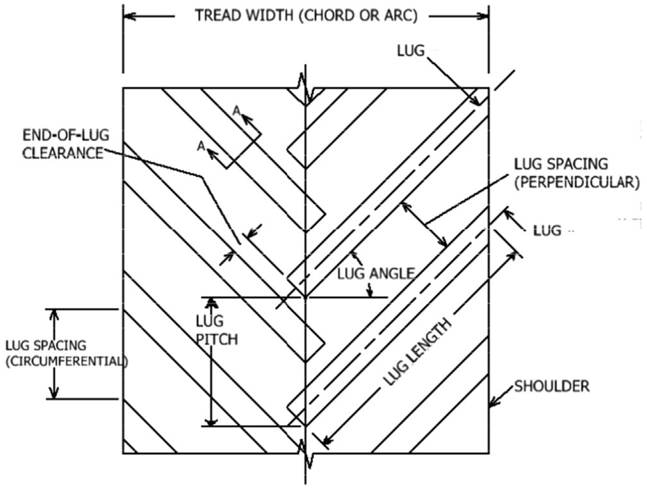


Fig. 14. Schematic of lug for lug definitions, top view. Reprinted from (ANSI/ASAE S296.5 DEC2003 (R2018), 2018) with permission of American Society of Agricultural and Biological Engineers.

tracks, while "grouser" is associated with steel traction element such as wheels and steel tracks (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.9. Lug angle*

The average angle between the centerline of the lug face and the normal to the circumferential centerline of the traction element (Fig. 14; ANSI/ASAE S296.5 DEC2003 (R2018), 2018)

2.11.10. Lug base*

The projected thickness or width of the lug at the points where the projected planes of the leading and trailing sides meet the projected undertread face (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.11. Lug face

The outermost surface of the lug (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.12. Lug fillet*

The curved section used to blend the sides of the lug into the undertread face (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.13. Lug height*

The distance measured from the undertread face to the lug face, also known as tread depth. (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018)

2.11.14. Lug length*

The curvilinear distance measured from end to end along the center line of the face of the lug (Fig. 14; ANSI/ASAE S296.5 DEC2003 (R2018), 2018)

2.11.15. Lug pitch*

The distance between the leading sides of adjacent lugs on the same side of a traction element measured at the center line (Fig. 14).

2.11.16. Lug sides

The surface of the lug between the undertread face and the lug face (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

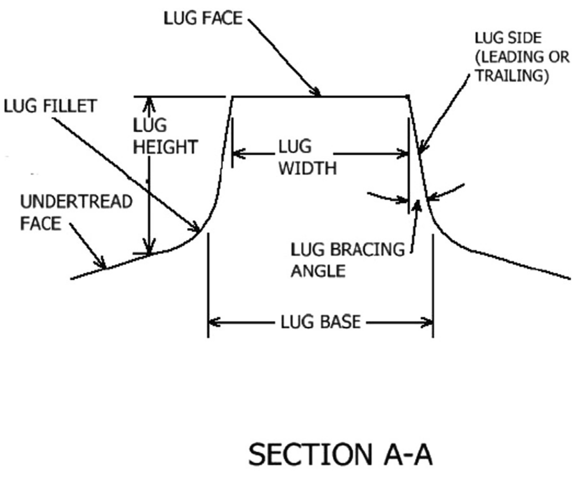


Fig. 15. Schematic of lug for lug definitions, side view. Reprinted from (ANSI/ASAE S296.5 DEC2003 (R2018), 2018) with permission of American Society of Agricultural and Biological Engineers".

2.11.17. Lug space, circumferential*

The distance from the leading side of a lug to the trailing side of the lug ahead of it, measured parallel to the center line of the traction element at the lug face (Fig. 14; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.18. Lug space, perpendicular*

The distance measured perpendicularly from the leading side of a lug to the trailing side of the lug ahead of it, measured at the lug face (Fig. 14; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.11.19. Lug width

The width of the face of the lug measured at right angles to the center line of the face of the lug (Fig. 15; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.12. M

2.12.1. Macrorelief

Large differences in relief that present significant obstacles to vehicle movement.

2.12.2. Mean free path

The average distance traveled by a vehicle, without stopping for any reason, in a number of trials in a specific terrain.

2.12.3. Microrelief*

Small differences in relief of commonly a few centimeters (this range may vary depending on the vehicle design) that are significant to vehicle ride. For example, the microrelief for a M113 armored personnel ranged roughly between 5 mm and 40 mm (Braunack, 1986).

2.12.4. Mobility (vehicle mobility)*

The ability of vehicle to traverse a terrain (Society of Automotive Engineers, 1967a).

2.12.5. Modeling approach*

In the context of off-road mobility and terramechanics study, the common modeling approaches are the empirical approach, semi-empirical approach, theoretical approach, and numerical approach.

(a) *Empirical approach*. A modeling approach purely based on the experimental test data; the experimental test data determines the mathematical form of model. Empirical model examples are the Bekker's pressure-sinkage model (Bekker, 1969) and the Brixius traction prediction equations (Brixius, 1987).
(b) *Semi-empirical or semi-analytical approach*. A modeling approach based on the combination of the experimental test data and theories of mechanics or theories of other branches of physics; the experimental test data and the theories applied determine the mathematical form of the model. A semi-empirical model example is the Reece's pressure-sinkage model (Reece, 1965).
(c) *Analytical approach (referred to as theoretical approach occasionally)*. A modeling approach based on theories of mechanics or theories of other branches of physics, experimental results are used to validate not to derive these models. A theoretical model example is the Load-Sinkage Analytical model Lyasko, 2010a).
(d) *Numerical approach*. A modeling approach that discretizes the modeling object as a group of elements. E.g., the finite element method (FEM) (Liu et al., 2000) and the discrete element method (DEM) (Nakashima and Oida, 2004).

It is worth mentioning that the boundaries between the aforementioned approaches are not uniformly and strictly defined. A mix of some of these approaches could be applied in modeling.

2.12.6. Modulus, Shear (modulus of elasticity), G**

The ratio of shear stress to the shear strain (Wulfsohn and Adams, 2002).

2.12.7. Modulus, Young's, E**

The ratio of stress to strain under uniaxial load (Wulfsohn and Adams, 2002). Also often referred to simply as the elastic modulus or modulus of elasticity (ASTM D653-14, 2014).

2.12.8. Mohr-Coulomb failure criterion**

See Coulomb's equation.

2.12.9. Mohr-Coulomb failure model**

See Coulomb's equation.

2.12.10. Moisture content*

Same as water content.

2.12.11. Motion resistance, external (external rolling resistance)*

The resistance to movement of a vehicle or a traction element provided by the surface on and through which it moves (Tripartite Working Group on Ground Mobility, 1961), due to the bulldozing effect (i.e., the bulldozing resistance), compacting the soil (i.e., the compaction resistance), and the component of shear stress on the contact area opposite to the direction of travel (Wong, 2009; Lyasko, 2010b).

2.12.12. Motion resistance, internal (internal rolling resistance)*

The resistance to movement of a vehicle or a traction element provided by the internal friction and impact of its moving parts and the energy losses in the traction elements, e.g., the energy dissipation in the hysteresis of tire material (Wong, 2008; Tripartite Working Group on Ground Mobility, 1961).

2.12.13. Motion resistance, total (total rolling resistance or motion resistance)*

The sum of internal and external motion resistance (Tripartite Working Group on Ground Mobility, 1961). For a vehicle or traction element in traction mode, the total motion resistance is also the difference of gross tractive effort and net tractive effort. For a transport element, a vehicle or traction element in towing mode, the total motion resistance is also called the towing force (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.12.14. Muck**

Well decomposed organic soil material with a low content of fibers (plant tissue excluding live roots) (Soil Science Division Staff, 2017); or stone, dirt, debris, or useless material; or an organic soil of very soft consistency (ASTM D653-14, 2014).

2.12.15. Muskeg*

Level, practically treeless areas of organic soil supporting dense growth consisting primarily of grasses. The surface of the soil is covered with a layer of partially decayed grass and grass roots which is usually wet and soft when not frozen (ASTM D653-14, 2014). The sublayer is peat of any depth and existing in association with various hydrological conditions.

2.13. N

2.13.1. Numeric, wheel**

Same as the cohesive-frictional soil-tire numeric (see soil-tire numeric).

2.13.2. Number, wheel mobility**

A dimensionless variable that is an empirical function of soil strength, tire load, and tire geometrical parameters, used as the input variable of the empirical models for net tractive effort coefficient, gross tractive effort coefficient, and motion resistance coefficient. Most of the wheel mobility numbers can be expressed as the product of wheel numeric and wheel mobility number coefficient which is also dimensionless (Taheri et al., 2015; Hegazy and Sandu, 2013).

$$N_{wheel} = N \times k_{wheel} \tag{7}$$

where N_{wheel} is the wheel mobility number, N is the wheel numeric, and k_{wheel} is the wheel mobility number coefficient.

2.13.3. Numeric, soil-tire**

A dimensionless variable that reflects the ratio of soil strength to a nominal pressure that a tire applies to a soil, calculated by using an empirical formula and input variables such as cone index, tire geometrical parameters, vehicle load, etc. Typical soil-tire numeric includes the clay-tire numeric, sand-tire numeric, and the cohesive-frictional soil-tire numeric (Freitag, 1965; Turnage, 1972; Wismer and Luth, 1973).

$$N_c = \frac{CIbd}{W} \times \left(\frac{\delta}{h}\right)^{1/2} \times \frac{1}{1 + (b/2d)} \tag{8}$$

$$N_s = \frac{G(bd)^{3/2}}{W} \times \frac{\delta}{h} \tag{9}$$

$$N_{cs} = \frac{CIbd}{W} \tag{10}$$

where N_c is clay-tire numeric, N_s is sand-tire numeric, N_{cs} is cohesive-frictional soil-tire numeric, b is tire section width, d is tire diameter, CI is cone index, h is unloaded tire section height, W is tire load, and δ is tire deflection.

2.14. O

2.14.1. Obstacle

A definable environmental feature that inhibits the movement of a vehicle (U.S. Department of Defense, 1968).

2.14.2. Obstacle, lateral

An unsurmountable terrain feature or a combination of such features that forces a vehicle to deviate laterally from a desired path (U.S. Department of Defense, 1968).

2.14.3. Obstacle, longitudinal

A surmountable terrain feature (e.g., tall, thick grass) that inhibits the movement of a surface vehicle by forcing it to slow down as the feature is negotiated (U.S. Department of Defense, 1968).

2.14.4. Obstacle, vertical

An obstacle that forces a vehicle to move in the vertical plane while surmounting it (U.S. Department of Defense, 1968).

2.14.5. Obstacle performance

The ability of a vehicle to negotiate a specified obstacle.

2.14.6. Off-road

Away from terrain specifically improved for vehicle use (U.S. Department of Defense, 1968).

2.14.7. On-road

On the terrain that is specifically paved and improved for vehicle use, such as asphalt lane.

2.14.8. Organic matter**

All decomposed, partially decomposed and undecomposed organic materials of plant and animal origin, and it is generally synonymous with humus, although humus is more commonly used when referring to the well-decomposed organic matter (Jahn et al., 2006) or the partially decomposed organic matter (ASTM D653-14, 2014).

2.15. P

2.15.1. Pararock fragment**

Piece of geologic or pedogenic material with an extremely weakly cemented to moderately cemented rupture-resistance class; a constituent of mineral soil (Soil Science Division Staff, 2017).

2.15.2. Particle size distribution (gradation)**

The proportions by dry mass of a soil distributed over specified particle-size ranges (ASTM D7928-17, 2017). Particle size distribution is usually presented in a tabular format or graphical format that is referred to as the particle-size distribution curve (percent passing versus logarithm of the particle size in mm) (ASTM D6913/D6913M-17, 2017).

Measurement methods for particle size distribution include the sieving method, the pipette method, and the hydrometer method. The sieving method works for coarse soils which only comprise gravel and sand. By contrast, the hydrometer method and pipette method are categorized as the sedimentation method which is targeted at fine-grained soils that consist of silt and clay. In many cases, the soil to be tested includes at least three of the gravel, sand, silt, and clay. To cope with such soil, the sieve method and sedimentation method are combined together to determine the particle size distribution.

For the standard measurement methods of particle size distribution, see (ASTM D6913/D6913M-17, 2017; ASTM D7928-17, 2017; ISO 11277:2009, 2009; ISO 17892-4:2016, 2016).

2.15.3. Peat**

Slightly decomposed organic soil material with a high content of original fibers, derived primarily from plant materials (ASTM D653-14, 2014; Soil Science Division Staff, 2017).

2.15.4. Peatland*

Areas having peat-forming vegetation on which peak has accumulated or is accumulating (ASTM D653-14, 2014).

2.15.5. Penetration resistance gradient**

Same as cone index gradient

2.15.6. Percent saturation, S^*

The ratio, expressed as a percentage, of the volume occupied by water in a given soil mass at a given temperature (usually 20 °C), V_w, to the total volume of intergranular space (voids); that is:

$$S = [V_w/(V_w + V_a)] \times 100 \tag{11}$$

where S is percent saturation, V_w is the volume occupied by water, and V_a is the volume occupied by air. (Fig. 11; ASTM D653-14, 2014).

2.15.7. Pitch

Same as angle of pitch.

2.15.8. Plasticity*

The property of material which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change (ASTM D653-14, 2014).

2.15.9. Plasticity index, PI^*

In cohesive soils, the range of water content over which a soil behaves plastically, which is the numerical difference between the liquid limit, LL, and the plastic limit, PL (ASTM D4318–17, 2017).

For measurement methods of plasticity index, see Atterberg limits.

2.15.10. Plastic limit, PL^*

In cohesive soils, the Atterberg limit (the water content, in percent) separating the semi-solid and plastic phases of soil (ASTM D653-14, 2014).

For measurement methods of plasticity limit, see Atterberg limits.

2.15.11. Ply, breaker*

The plies whose cords run approximately parallel to the plane of the tire's cross section and do not tie into the beads of the bias-ply tires (ANSI/ASAE S296.5 DEC2003 (R2018), 2018)

2.15.12. Ply rating

An index of strength that does not necessarily represent the number of cord plies in the tire. It identifies a given tire with its maximum recommended load when used in a specific type of service (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.15.13. Porosity, n

The ratio, expressed as a percentage, of the volume of voids of a given soil mass to the total volume of the soil mass, V; that is:

$$n = [(V_a + V_w)/V] \times 100 \tag{12}$$

where n is porosity, V_a is the volume occupied by air, and V_w is the volume occupied by water. (Fig. 11; ASTM D653-14, 2014).

2.15.14. Poisson's ratio, ν^*

Ratio between linear strain changes perpendicular to and in the direction of a given uniaxial stress change (ASTM D653-14, 2014).

2.15.15. Power number, PN^*

The power supplied at the drive axles per unit of vertical load and vehicle forward velocity (Freitag et al., 1970):

$$PN = \frac{T\omega}{Wv} \tag{13}$$

where PN is power number, T is torque input to the traction elements, ω is rotational velocity of the torque input shaft, W is gross vehicle weight, and v is vehicle forward velocity.

2.16. R

2.16.1. Rebound*

The relative displacement of the sprung and unsprung masses in a suspension system in which the distance between the masses increases, as illustrated in Fig. 16 (Society of Automotive Engineers, 2008).

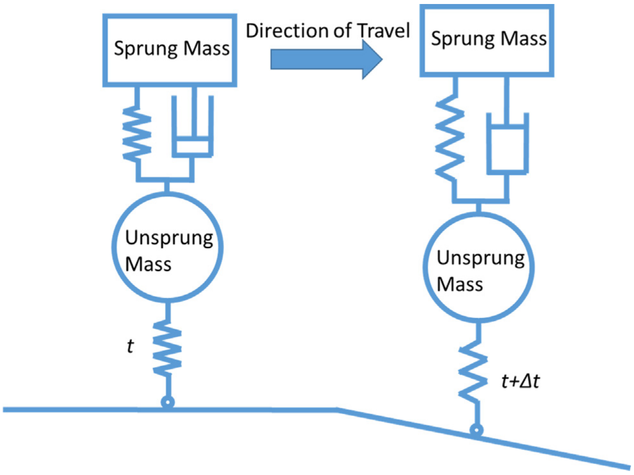


Fig. 16. Schematic illustrating rebound.

2.16.2. Recognition distance

The maximum distance at which a vehicle driver can see and recognize objects that may be hazardous to his vehicle or to himself (The Staffs of the Surface Mobility Division (TACOM) and the Mobility and Environmental Laboratory (WES), 1973).

2.16.3. Rating cone index, RCI*

The measured cone index multiplied by the remolding index; it expresses the soil-strength rating of soil under repeated vehicular traffic.

2.16.4. Relative density, D_d*

The ratio of the difference between the void ratio of a cohesionless soil in the loosest state, e_{max}, and any given void ratio, e, to the difference between the void ratios in the loosest state, e_{max}, and in the densest state, e_{min}; that is:

$$D_d = (e_{max} - e)/(e_{max} - e_{min}) \tag{14}$$

where D_d is relative density (ASTM D653-14, 2014).

Alternatively, the relative density can be also defined by (ASTM D653-14, 2014)

$$D_d = \frac{\rho_{d,\,max}}{\rho_d} \times \frac{\rho_{d,\,max} - \rho_d}{\rho_{d,\,max} - \rho_{d,\,min}} \tag{15}$$

where $\rho_{d,\,\max}$ is maximum dry density, $\rho_{d,\,\min}$ is minimum dry density, and ρ_d is any given dry density.

For the standard measurement methods of relative density, see (ASTM D4254-16, 2016).

2.16.5. Reliability

The probable distance or time of operation between failures of a vehicle or vehicle component.

2.16.6. Remolded soil*

Soil that has had its natural structure modified by manipulation or shear distortion (destructured) while attempting to maintain constant water content and density; the remolded soils are typically cohesive soils that are not friable or brittle, can be kneaded in a rubber membrane, and reformed in to a testable shape (ASTM D653-14, 2014).

2.16.7. Remolding

The manipulation or working of a soil by traffic or other means.

2.16.8. Remolding index, RI*

The ratio of the cone index of a soil after remolding to the pre-remolding cone index of the soil, determined by the remolding test (Mobility and Environmental Systems Laboratory (U.S.), 1958; Stevens et al., 2013; see remolding equipment in Section 3). This ratio expresses the change in soil strength that may occur under vehicular traffic (U.S. Army Engineer Waterways Experiment Station, 1955).

2.16.9. Remolding test (remold test)**

A test to determine the remolding potential of a soil. In this test, an undisturbed soil sample is collected and transferred to a remold cylinder. The soil is compacted by using a drop hammer if the soil is fine-grained or by dropping the remold cylinder if the soil is coarse-grained with fines. Cone index is measured before and after this compaction effort (Meyer and Knight, 1961; Mobility and Environmental Systems Laboratory (U.S.), 1958; see remolding equipment in Section 3).

2.16.10. Ride

The qualitative and/or quantitative evaluation of the oscillatory motions of the vehicle.

2.16.11. Rim diameter

The diameter at the lip of the rim flange (Fig. 17; McRae et al., 1965). The rim diameter defined in (ANSI/ASAE S296.5 DEC2003 (R2018), 2018) is the same as the nominal rim diameter defined in this document.

2.16.12. Rim diameter, nominal

The diameter at the shoulder of the rim. It is the rim diameter that appears in the designation of the tire size (e.g. the “16” in the ”6.00-16”) (Fig. 17; McRae et al., 1965). The nominal rim diameter defined here is the “rim diameter” defined in (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.16.13. River*

A hydrologic geometry feature that channels water flow. To provide guidance for uniform usage, the following tentative minimum dimensions must be satisfied for the feature to be considered a river at the cross section under consideration:

Width of water surface: 6.1 m (20 ft.)
Depth: 150 mm (6 in.).

2.16.14. Roll

Same as angle of roll.

2.16.15. Rock fragment**

Piece of geologic or pedogenic material with a strongly cemented or more cemented rupture-resistance class; a constituent of mineral soil (Soil Science Division Staff, 2017).

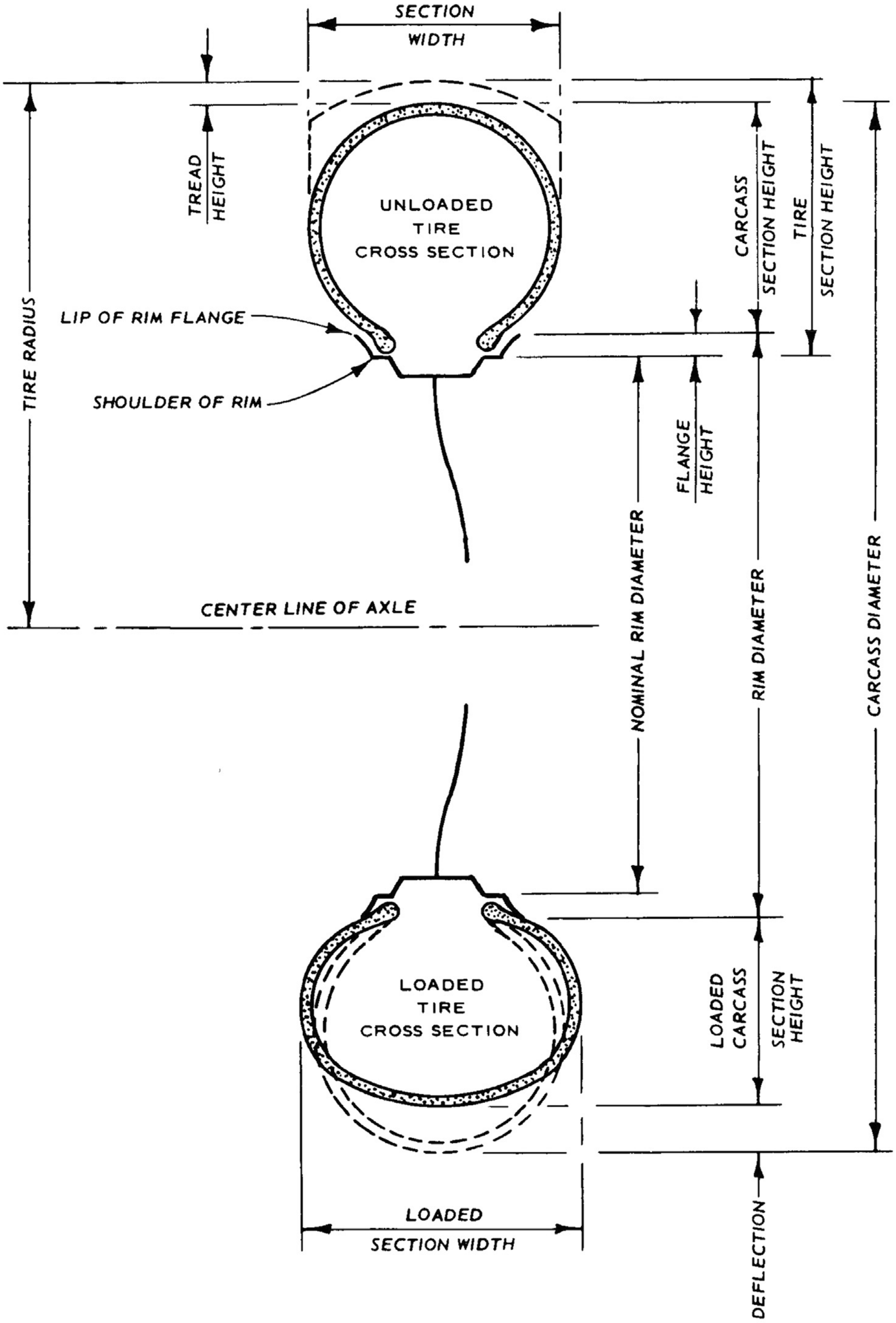
2.16.16. Rolling circumference*

The longitudinal distance traveled under the specified zero condition by the wheel, tire, or the drive axle of track in one complete revolution. The rolling circumference may vary with changes in load, speed, soil condition, or tire pressure.

2.16.17. Rolling radius, r_R*

Rolling circumference divided by 2π. It is suggested that the zero condition used to define rolling radius/rolling circumference be stated (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

In some publications (Kiss, 2003; Day, 2014), the rolling radius of a tire is defined the same as the tire loaded radius in this document.



NOTE: PERCENT DEFLECTION = $\frac{\text{DEFLECTION}}{\text{CARCASS SECTION HEIGHT}} \times 100.$

Fig. 17. Schematic of tire, cross section view.

*2.16.18. Rolling radius, effective***

Quotient of the longitudinal speed (forward speed) of the tire or wheel center or the drive axle of track divided by the angular speed of the tire or wheel or the drive axle of track. Effective rolling radius can be defined in traction, braking, and towing mode (Pacejka, 2005; Wong, 2008). Effective rolling radius is also referred to as effective tire radius (Rajamani, 2012), kinematic rolling radius (Kiss, 2003), effective radius, or rolling radius (Jazar, 2014). Although referred to as rolling radius (Jazar, 2014), the effective rolling radius should not be confused with the rolling radius. Rolling radius is a special case of effective rolling radius under a zero condition (see zero condition).

*2.16.19. Rolling resistance, external, internal and total, R**

Rolling resistance is the same as motion resistance, yet preferably referred to as motion resistance (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.16.20. Rut**

A track where sinkage occurs and channels form, due to the traffic of a traction element, or other pressure sources, e.g., a plate (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.16.21. Rut Depth**

See sinkage, residual.

2.17. S

2.17.1. Self-propelled condition**

The condition in which the vehicle or traction element is just able to propel itself, i.e., zero drawbar pull or net tractive effort (Zoz and Grisso, 2003).

2.17.2. Self-propelled point

Same as self-propulsion point.

2.17.3. Self-propulsion point (self-propelled point)*

The point on a drawbar pull-slip/net traction-slip curve at which the vehicle or traction element is just able to propel itself, i.e., zero drawbar pull or net tractive effort (Tripartite Working Group on Ground Mobility, 1961; Zoz and Grisso, 2003).

2.17.4. Shear deformation modulus, K**

The reciprocal of the coefficient of the shear displacement term in the empirical or semi-empirical pressure-sinkage equation with a form similar to the Janosi and Hanomoto's shear stress-shear displacement equation:

$$\tau = \tau_s[1 - \exp(-j/K)] \tag{16}$$

where τ is shear stress, τ_s is shear strength (the maximum shear stress), j is shear displacement, and K is shear deformation modulus.

2.17.5. Shear resistance**

See internal friction.

2.17.6. Shear strength, τ_s, s

The maximum resistance of a soil to shearing stresses (ASTM D653-14, 2014).

2.17.7. Shear test**

A test in which a device induces shearing motion within the soil (e.g., by using a shear plate with grousers) or on the interface of the soil and a shear tool (e.g., by using a shear plate coated with metal, rubber, or other material), to determine the shear strength of soil or the shear stress-shear displacement (shear deformation) relationship. The test device can be the shear vane, Bevameter, shear plate, direct shear device, triaxial test apparatus, etc., as described in Section 3.

2.17.8. Shrinkage index, SI**

The numerical difference between the plastic and shrinkage limits (ASTM D653-14, 2014).

For measurement methods of shrinkage index, see Atterberg limits.

2.17.9. Shrinkage limit, SL*

The Atterberg limit separating the solid and semi-solid phases of soil, which is the maximum water content at which a reduction in water content will not cause a decrease in volume of the soil mass (ASTM D653-14, 2014).

For measurement methods of shrinkage limit, see Atterberg limits.

2.17.10. Sinkage, z*

In the context of off-road mobility and terramechanics study, the deformation of the supporting surface from its original, undisturbed surface (before the traffic), measured normal to the direction of travel; the sinkage results from the supporting surface being subjected to pressure (during the traffic) from a pressure source, e.g., a tire, a wheel, a plate, a track, etc.

2.17.11. Sinkage, critical vehicle

The sinkage (instantaneous rut depth) at which a vehicle slip-stalls (Tripartite Working Group on Ground Mobility, 1961).

2.17.12. Sinkage, dynamic**

The sinkage caused by the normal load and shearing motion of the pressure source (Society of Automotive Engineers, 1967b). The dynamic sinkage is considered to be the sum of static sinkage and slip sinkage (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.17.13. Sinkage, residual (rut depth)*

The depth of the rut (from original surface to bottom) in the path left by a vehicle, traction element, or other pressure sources (Tripartite Working Group on Ground Mobility, 1961). The bottom may need to be clarified in a study as to whether it is the bottom left by the tread, lug, or groove.

2.17.14. Sinkage, slip**

The sinkage caused by the shearing motion of the pressure source. If the pressure source is a tire, wheel, or track, the shearing motion occurs during the steering or slippage of the tire, wheel, or track.

2.17.15. Sinkage, static**

The sinkage produced by the normal load of the pressure source. It is also the sinkage when no shearing motion of the pressure source occurs.

2.17.16. Sinkage, tire (or wheel, or track, or plate)**

The sinkage at the lowest point of the contact interface (contact patch) between soil and tire (or wheel, or track, or plate). The lowest point may need to be clarified in a study as to whether it is on the tread, lug, or groove.

2.17.17. Sinkage exponent, n*

The exponent of the sinkage term in the empirical or semi-empirical pressure-sinkage equation with a form similar to the Bekker's pressure-sinkage equation, Eqs. (17) and (18) (Bekker, 1969).

$$p = kz^n \tag{17}$$

$$k = \left(\frac{k_c}{b} + k_\phi\right) \tag{18}$$

where b is the smaller dimension of the contact patch, k is the sinkage modulus, k_c is the part of the sinkage modulus influenced by soil cohesion, k_ϕ is the part of the sinkage modulus influenced by soil friction angle, and n is the sinkage exponent.

2.17.18. Sinkage modulus, k*

The coefficient of the sinkage term in the empirical or semi-empirical pressure-sinkage equation with a form similar to the Bekker's pressure-sinkage equation.

2.17.19. Sinkage test (load sinkage test, pressure-sinkage test, or penetration test)**

A test in which a plate or a cone penetrometer penetrates the soil at a constant penetration rate, and the penetration resistance and penetration depth (sinkage) are simultaneously recorded.

2.17.20. Skid, S*

A slip indicator normally utilized for a braked wheel, tire, or track. Using the terms defined under slip, skid is defined mathematically as (Wong, 2009)

$$S = \frac{v - r_R\omega}{v} \tag{19}$$

where S is skid, r_R is rolling radius, ω is angular velocity of the wheel, or number of revolutions per unit time multiplied by 2π for a track, and v is forward velocity of vehicle or wheel axle.

2.17.21. Slip (slippage)**

The relative motion between a traction element and the supporting surface. The slip in the opposite direction to the direction of travel is required to generate traction; if being excessive, such slip leads to a significant slowdown of the vehicle, i.e., a loss of tractive effort and vehicle speed, inability to achieve predefined goals, or, in the worst case, getting entrapped without the possibility of recovery (Gonzalez and Iagnemma, 2018). The slip in the same direction as the direction of travel contributes to the motion resistance.

2.17.22. Slip, lateral (sideslip)**

The slip in the lateral direction, in general characterized by the tangent of slip angle.

2.17.23. Slip, longitudinal**

The slip in the longitudinal direction, in general characterized by slip ratio.

2.17.24. Slip angle (sideslip angle)**

The angle formed between the direction of tire or wheel travel and the line of intersection of the center plane of the tire or wheel with the supporting surface (Wong, 2008).

2.17.25. Slip ratio (travel reduction), i*

An indication of how the speed of the traction elements differs from the forward speed of the vehicle. Slip ratio is defined by the equation:

$$i = \frac{r_R\omega - v}{r_R\omega} \tag{20}$$

where i is slip ratio, r_R is rolling radius, ω is angular velocity of the wheel, or number of revolutions per unit time multiplied by 2π for a track, and v is forward velocity of vehicle or wheel axle.

Alternatively, slip ratio is defined by replacing the rolling radius in the equation above with tire unloaded radius (Jazar, 2014) or by replacing the denominator of the equation above, $r_R\ \omega$, with v (Pacejka, 2005).

The definition of slip ratio above is commonly used for acceleration (traction mode). During braking (braking mode), slip ratio is defined by replacing the denominator of the equation above, $r_R\ \omega$, with v, (Rajamani, 2012).

Note that in the ASABE standard (ANSI/ASAE S296.5 DEC2003 (R2018), 2018), slip ratio is defined as one minus the ratio of the distance traveled per revolution of the traction element under operating conditions, to distance travelled per revolution under the specified zero condition; this definition is equivalent to the equation above.

Also note that the slip ratio is occasionally referred to as longitudinal slip or slip for short (Pacejka, 2005; Gonzalez and Iagnemma, 2018).

2.17.26. Slipperiness

A soil condition of deficient traction capacity in a thin surface layer of a soil which is otherwise trafficable (U.S. Department of Defense, 1968).

2.17.27. Slope (grade)*

The tangent of the angle that a surface makes with the horizontal, expressed as a percentage.

2.17.28. Slope facet

A surface that is at essentially the same angle with the horizontal for a determinable area (USAE Waterways Experiment Station, 1963).

2.17.29. Slope (lateral) stability

The steepest slope that the fully loaded vehicle can traverse slowly on a course perpendicular to the direction of the slope without overturning, measured in percent or degrees (U.S. Army Transportation Combat Developments Agency, 1962).

2.17.30. Slope length*

The linear distance from one change of slope to another (measured along the slope).

2.17.31. Slope performance

The ability to negotiate a specified uniform slope, unaided. (The type of slope, i.e. concrete, earth, grass-covered, etc., should be stated as should be the state of the traction elements, i.e. bare wheels, wheels with chains, tracks with pads, etc.)

2.17.32. Snow density

The weight of snow solids per unit of total volume of snow mass.

2.17.33. Soft terrain performance*

The ability of a vehicle, traction element or transport element to operate on a soft yielding soil, snow or muskeg, usually expressed as relations between certain significant vehicle performance indicators and terrain-vehicle system parameters such as soil, snow, or muskeg consistency and traction element dimensions, etc.

2.17.34. Soil*

Sediments and other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter (ASTM D653-14, 2014). In the context of terrain-vehicle mechanics literature, the term soil may include snow, ice, peat, coarse surface fragments (Jahn et al., 2006), and other surface materials.

2.17.35. Soil, mineral**

A soil that primarily consists of mineral matter. The primary constituents of mineral soil are fine earth, rock fragment, pararock fragments, discrete artifacts (Soil Science Division Staff, 2017). For a complete description of mineral soil see (Soil Survey Staff, 1999).

2.17.36. Soil, organic*

A soil with a high organic content. In general, organic soils are very compressible and have poor load-sustaining properties (ASTM D653-14, 2014). For a complete description of organic soil see (Soil Survey Staff, 1999).

*2.17.37. Soil failure***

Plastic deformation of an over-consolidated soil subject to shear, causing dilation and a decrease in strength (ASTM D653-14, 2014). Soil failure can lead to traction loss, vehicle slippage, or even vehicle entrapment (Gonzalez and Apostolopolous, 2019).

*2.17.38. Soil friction angle***

See angle of internal friction.

*2.17.39. Soil particle size classification system***

A system which identifies soil particle size classes (soil separates or fractions), e.g., sand, silt, clay, etc. Various soil particle size classification systems exist, commonly used ones are:

1. American Association of State Highway and Transportation Officials, AASHTO (AASHTO M 145-91 (2012), 2012)
    - Silt or clay: smaller than 0.075 mm dia.
    - Sand, fine: 0.075–0.425 mm dia.
    - Sand, coarse: 0.425–2 mm dia.
    - Gravel: 2–75 mm dia.
2. Food and Agriculture Organization of the United Nations, FAO (Jahn et al., 2006)
    - Clay: smaller than 0.002 mm dia.
    - Silt, fine: 0.002–0.02 mm dia.
    - Silt, coarse: 0.02–0.063 mm dia.
    - Sand, very fine: 0.063–0.125 mm dia.
    - Sand, fine: 0.125–0.2 mm dia.
    - Sand, medium: 0.2–0.63 mm dia.
    - Sand, coarse: 0.63–1.25 mm dia.
    - Sand, very coarse: 1.25–2 mm dia.
    - Gravel: greater than 2 mm dia.
3. International Society of Soil Science Textural Soil Classification System, ISSS (International Society of Soil Science, 1929)
    - Clay: smaller than 0.002 mm dia.
    - Silt: 0.002–0.02 mm dia.
    - Sand, fine: 0.02–0.2 mm dia.
    - Sand, coarse: 0.2–2 mm dia.
    - Gravel: greater than 2 mm dia.
4. Unified Soil Classification System, Unified or ASTM (ASTM D2487-17, 2017)
    - Silt or clay: smaller than 0.075 mm dia.
    - Sand, fine: 0.075–0.425 mm dia.
    - Sand, medium: 0.425–2 mm dia.
    - Sand, coarse: 2–4.75 mm dia.
    - Gravel: greater than 4.75 mm dia.
5. U.S. Department of Agriculture Textural Soil Classification System, USDA (Soil Science Division Staff, 2017)
    - Clay, fine: smaller than 0.0002 mm dia.
    - Clay, coarse: 0.0002–0.002 mm dia.
    - Silt, fine: 0.002–0.02 mm dia.
    - Silt, coarse: 0.02–0.05 mm dia.
    - Sand, very fine: 0.05–0.1 mm dia.
    - Sand, fine: 0.1–0.25 mm dia.
    - Sand, medium: 0.25–0.5 mm dia.
    - Sand, coarse: 0.5–1 mm dia.
    - Sand, very coarse: 1–2 mm dia.
    - Gravel: greater than 2 mm dia.

2.17.40. Soil strength

The resistance of a soil to an applied stress. The strength varies with moisture content and the nature, arrangement, and size distribution of the soil particles, and the test itself.

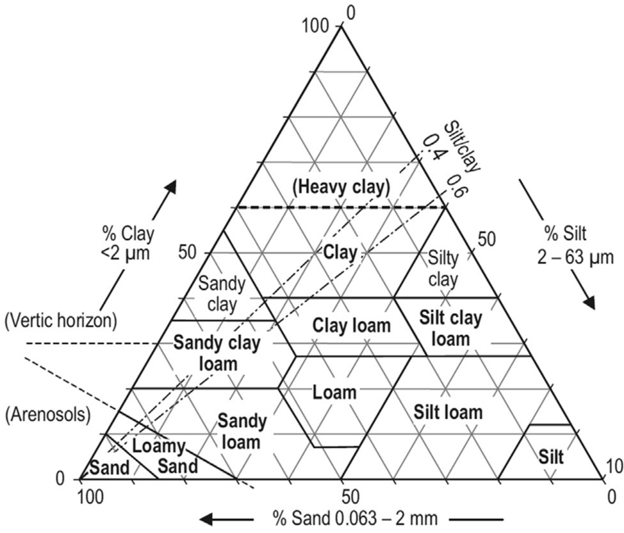


Fig. 18. FAO soil textural triangle. Reprinted from (Jahn et al., 2006) with permission of the Food and Agriculture Organization of the United Nations.

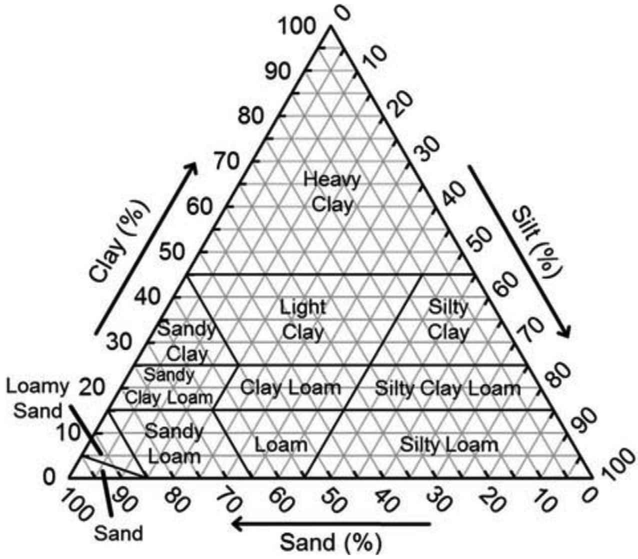


Fig. 19. ISSS soil textural triangle (Murano et al., 2015). Reprinted from (Murano et al., 2015) with permission of the Taylor & Francis.

*2.17.41. Soil texture***

The weight proportion of the various soil particle size classes (Jahn et al., 2006). Soil texture is described as soil textural class or soil texture class (see soil texture classification system).

In (ASTM D653-14, 2014), the soil texture is defined the same as gradation.

*2.17.42. Soil texture classification system***

A system identifies the soil texture class based on the values for the weight proportion of the various soil particle size classes and occasionally on the values for other soil parameters, e.g., plasticity index in (ASTM D2487-17, 2017). Multiple soil texture classification systems exist and can be presented in a flowchart, a table, or a soil textural triangle (Figs. 18, 19, and 20); commonly used soil texture classification systems are:

1. American Association of State Highway and Transportation Officials, AASHTO, Table 1 of (AASHTO M 145-91 (2012), 2012)

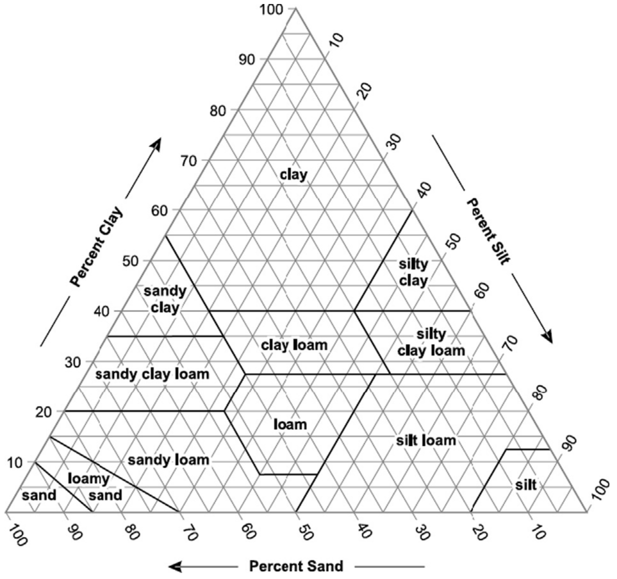


Fig. 20. USDA soil textural triangle. Reprinted from (Soil Science Division Staff, 2017) with permissions of the USDA.

2. Food and Agriculture Organization of the United Nations, FAO (Jahn et al., 2006)
3. International Society of Soil Science Textural Soil Classification System, ISSS (International Society of Soil Science, 1929)
4. Unified Soil Classification System, Unified or ASTM, as described in Figs. 1-3 of (ASTM D2487-17, 2017)
5. U.S. Department of Agriculture Textural Soil Classification System, USDA (Soil Science Division Staff, 2017)

2.17.43. *Soil trafficability**

The capacity of soil to withstand the passage of vehicles. The rating cone index minus the vehicle cone index can be a measure of soil trafficability.

2.17.44. *Specific Gravity, Soil, G_s***

The ratio of the wet bulk density of soil, γ_w, to the density of water, γ_{water}, (Muro and O'Brien, 2004)

$$G_s = \frac{\gamma_w}{\gamma_{water}} \tag{21}$$

where G_s is the soil specific gravity.

For the standard measurement method of specific gravity, see (ASTM D854-14, 2014; ASTM D5550-14, 2014)

2.17.45. *Specific Weight***

Same as unit weight

2.17.46. *Speed made good*

The straight line distance between two points divided by the time required to go between the two points regardless of path.

2.17.47. *Spring rate**

See stiffness.

2.17.48. *State-of-the-ground*

A standardized surface synoptic observation which describes the condition of the ground surface. Basically, the states-of-the-ground are recognized as dry, moist, wet, frozen, and ice or snow covered. The system has been used by the World Meteorological Organization since its creation in 1950 and by its predecessor, the International Meteorological Organization, since 1923 (U.S. Department of Defense, 1968).

2.17.49. *Steering types**

i. Articulated. A system used by tracked or wheeled vehicles consisting of two or more powered units in which the turning maneuver is accomplished by yawing the units with respect to each other about a pivot system not located over an axle of either unit (U.S. Army Material Command, 1965).
ii. Conventional (Ackerman). A system whereby the steering of wheeled vehicle is such that, as far as possible, the axes of all axles meet at a common point (Tripartite Working Group on Ground Mobility, 1961).
iii. Coordinated steer**. A steering system where the two front wheels (on the same axle steer) rotate about their own respective steering axes/kingpin axes (Fig. 21). Note that the steering angles of the front wheels are linked or coordinated by a mechanical linkage. If more than one axle is steering, it is possible that the steering angles of the respective wheels are independent of one another or occasionally may be coordinated through an alternative mechanical linkage (Genta, 2010). If meeting the criterion about the axes of all axles as described above, coordinated steering can be Ackerman steering.
iv. Skid steer (slip steer)*. A system whereby tracked and wheeled vehicles are steered when the tracks or wheels have no angular freedom in relation to the vehicle hull; changing the relative speeds of the running gear on each side of the vehicle produces differential traction and hence affects the steering. There are few methods for achieving differential traction. Taking the wheeled vehicles for example, the first method is placing independent motors in the wheels of the vehicle. The second method is that two motors actuate the wheels of the two sides independently. The third method is using a differential gear. The fourth method is applying the brakes in differential mode. A small trajectory curvature radius can be accomplished by the skid steer; turning on the spot is possible by setting the rotation speeds of two sides equal yet opposite (Genta, 2010). The skid steer is further defined by the types of turns:
    1. Free. The turn obtained when the drive to one side is disengaged, but the other side is not braked (Tripartite Working Group on Ground Mobility, 1961).
    2. Neutral. A turn obtainable in some steering systems with the gearbox in neutral (Tripartite Working Group on Ground Mobility, 1961).
    3. Pivot. A turn about a vertical axis through the center of the vehicle when the speed of the drive on each side of the vehicle is equal in magnitude but opposite in sense (Tripartite Working Group on Ground Mobility, 1961).
    4. Power. A turn in which both sides are positively driven at different speeds (Tripartite Working Group on Ground Mobility, 1961).
    5. Slide. The turn obtained when the movement of the running gear of one side of the vehicle is stopped (Tripartite Working Group on Ground Mobility, 1961).
v. Regenerative steer*. A system whereby the wheels and tracks on each side of the vehicle are connected together mechanically, hydraulically, or electrically, such that a turning moment can be applied to the vehicle by differential application of torque.
vi. Wagon steer*. Steering of a vehicle consisting of one or more units by a single pivot system with the pivot point located over the front axle (U.S. Army Material Command, 1965).
vii. Independent**. All four wheels, for which the two front and two rear wheels either on the same axle or on more than one axle, are able to steer independently of one another about the steering axis/kingpin axis. The Ackerman condition is

dependent on the steering control of the vehicle. Implying that in a case where large steering angles are possible and the control of the vehicles system is flexible enough, meaning that any trajectory can be obtained (including all kind of maneuvers such as turning on the spot), is possible when using this kind of steering system (Genta, 2010).

2.17.50. Stem diameter

The diameter of the tree stem at armpit height of the 50 percentile man, approximately 1.30 m (4–1/4 feet).

2.17.51. Stem spacing, S_m

The average distance between tree stems. This value is computed from the number of stems per unit area, assuming that the stems are arranged in a hexagonal pattern (The Staffs of the Surface Mobility Division (TACOM) and the Mobility and Environmental Laboratory (WES), 1973). For ease of computation the following approximate equation is usually employed:

$$S_m = \frac{D}{N} \tag{22}$$

where S_m is stem spacing, D is diameter of structural cell, and N is number of stems in the structural cell.

2.17.52. Stem spread

Maximum distance across stem buttresses or above-ground roots within the height layer occupied by a vehicle.

2.17.53. Step height

The perpendicular height of a step on a slope facet (Fig. 22).

2.17.54. Sticky limit, T_w

The lowest water content at which a soil will stick to a metal blade drawn across the surface of the soil mass (ASTM D653-14, 2014).

*2.17.55. Stiffness (spring rate)***

The ratio of change of force (or torque) to the corresponding change in translational (or rotational) deflection of an elastic element (ASTM D653-14, 2014).

*2.17.56. Stiffness, cornering***

The negative of the first derivative of lateral force (Fig. 10) with respect to slip angle, usually evaluated at zero slip angle (Society of Automotive Engineers, 2008).

*2.17.57. Stiffness, driving or braking***

The first derivative of net tractive effort (the longitudinal force in Fig. 10) with respect to longitudinal slip, usually evaluated at zero longitudinal slip (Society of Automotive Engineers, 2008).

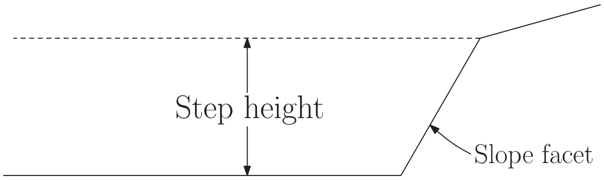


Fig. 22. Schematic of slope.

2.17.58. Stream

A hydrologic geometry feature that channels water flow but does not meet the minimum requirements to be considered a river.

2.17.59. Structural cell

A circular area in which the population of a selected structural element has a characteristic abundance. In mobility practice it is normally the circular area containing 20 members of a selected structural element.

2.17.60. Structural element

A population of plants consisting of members all of which are physiognomically similar in terms of a specific descriptive system.

2.17.61. Structural type

The population of a particular plant form having common structural elements and/or parameters (Mills and Clagg, 1964).

2.17.62. Surface effect vehicle, SEV

Same as air-cushion vehicle.

2.17.63. Surface geometry

The three-dimensional configuration of the terrain surface (U.S. Department of Defense, 1968).

2.17.64. Surge

Linear motion of a vehicle parallel to the X-axis (Fig. 6).

2.17.65. Sway

Linear motion of a vehicle parallel to the Y-axis (Fig. 6).

2.17.66. Sweep area (swept area)

The total projected area covered by a vehicle negotiating a turning maneuver.

2.17.67. Swept area

Same as sweep area.

2.17.68. Swimming capability

The ability of a vehicle with an inherent floating capability to steer and propel itself while floating across a water obstacle.

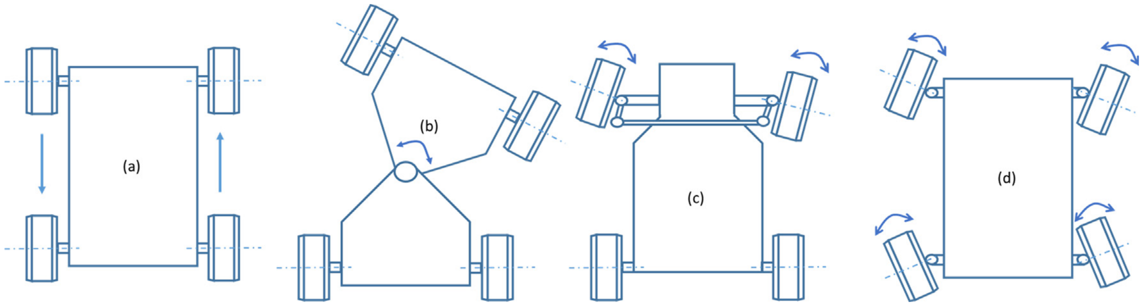


Fig. 21. Steering of a wheeled rover or vehicle: (a) skid steering; (b) articulated steering; (c) coordinated steering, (d) independent steering, in agreement with the one from (Genta, 2010).

2.18. T

2.18.1. Terrain

The physical environment of the earth, man-induced or natural, of a non-meteorological nature.

2.18.2. Terrain break angle

The angle between two adjacent slope facets.

2.18.3. Terrain factor (terrain feature)

A specific attribute of the terrain that can be described in quantitative terms (U.S. Department of Defense, 1968).

2.18.4. Terrain feature

Same as terrain factor.

2.18.5. Terrain profile

A geometric representation of a terrain surface as an elevation-distance curve (U.S. Department of Defense, 1968).

2.18.6. Terrain trafficability (trafficability)

The ability of terrain to support the passage of vehicles (U.S. Department of Defense, 1968).

2.18.7. Terrain type

A region throughout which a specific assemblage of factors occurs (U.S. Department of Defense, 1968). Some terrain types relevant in the off-road mobility study are desert, forest, open country.

2.18.8. Thixotropy

The property of a soil that enables it to increase in strength with time and unchanged water content. The process is reversible in that agitation or manipulation will cause a decrease in strength.

2.18.9. Tire, belted

A tire which has plies in a circumferential direction.

2.18.10. Tire, diagonal ply (conventional)

Tire construction in which the cords of the body plies run diagonally from bead to bead (Fig. 23).

2.18.11. Tire, radial ply

A tire whose cords in general run in both radial and circumferential directions (Fig. 24).

2.18.12. Tire carcass diameter

The outside diameter, exclusive of tread, of the inflated, but unloaded tire. Equals the rim diameter plus twice the carcass section height (Fig. 17; McRae et al., 1965).

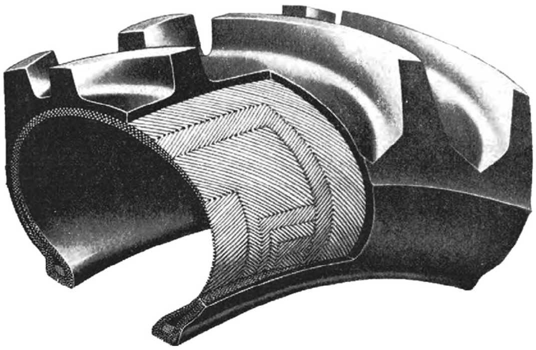


Fig. 23. Diagonal ply tire.

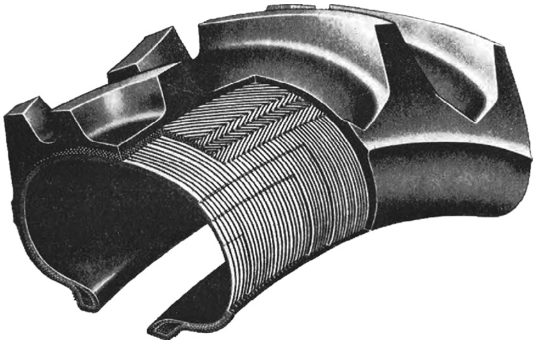


Fig. 24. Radial ply tire.

2.18.13. Tire carcass section height, loaded*

The minimum distance from the lowest point on the lip of the rim flange to the deepest point of the supporting surface on which the loaded tire is resting, exclusive of tread height (Fig. 17; McRae et al., 1965).

2.18.14. Tire carcass section height (unloaded tire carcass section height)

The distance from the lip of the rim flange to the periphery of the tire, exclusive of tread, measured along the vertical center line of the cross section of the inflated but unloaded tire (Fig. 17; McRae et al., 1965).

2.18.15. Tire contact area (tire contact patch)*

The portion of a tire in contact with the supporting surface. Interruptions of the contact area due to tread patterns or lugs are considered part of the contact area (McRae et al., 1965). In some literature, e.g., the ASABE standard (ANSI/ASAE S296.5 DEC2003 (R2018), 2018), tire contact area is the projection of the aforementioned portion to a plane parallel to the undisturbed supporting surface.

2.18.16. Tire contact length

The maximum length of the tire contact area, measured parallel to the plane of rotation of the tire (McRae et al., 1965).

2.18.17. Tire contact pressure (tire ground pressure)*

The actual pressure exerted vertically on the ground surface (e.g., soil surface or non-deforming surface) by the tire (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.18. Tire contact width (tread width)

The maximum width of the tire contact area, measured perpendicular to the plane of rotation of the tire (McRae et al., 1965).

2.18.19. Tire deflection

Any inward radial displacement of a point on the tire surface from its position on the inflated but unloaded tire, unless otherwise specified (Fig. 17); also the difference between the unloaded tire section height and the loaded tire section height at a given load and inflation pressure (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.20. Tire deflection, maximum hard surface

The difference between carcass section height and the loaded carcass section height (Fig. 17; McRae et al., 1965).

2.18.21. Tire deflection, maximum in-soil deflection

The maximum deflection measured radially on the center line of the cross section of the tire as it moves in the soil (McRae et al., 1965).

2.18.22. Tire diameter

The outside diameter, including tread, of the inflated but unloaded tire. Equals the carcass diameter plus twice the tread height at the center line of the cross section. In Fig. 17, one half of the tire diameter, i.e. the tire radius, is shown (McRae et al., 1965).

2.18.23. Tire inflation pressure

For air-filled tires, it is the gauge pressure measured with the valve in any position. For tires containing liquid, it is the gauge pressure measured with an "air water" gauge while the valve is in the bottom position (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.24. Tire loaded radius**

The radial distance, measured vertical to the direction of travel, from the wheel rotation axis to the lowest point of the contact area; the lowest point of the contact area has the largest soil deformation, vertical to the direction of travel, with respect to the undisturbed surface.

2.18.25. Tire moments**

The external moments acting on the tire, applied by the road, having the following components (Society of Automotive Engineers, 2008):

i. Overturning moment. The component of the tire moment vector tending to rotate the tire about the X_T-axis, positive clockwise when looking in the positive direction of the X_T-axis (Fig. 10).
ii. Rolling resistance moment. The component of the tire moment vector tending to rotate the tire about the Y_T-axis, positive clockwise when looking in the positive direction of the Y_T-axis (Fig. 10).
iii. Aligning torque (aligning moment). The component of the tire moment vector tending to rotate the tire about the Z_T-axis, positive clockwise when looking in the positive direction of Z_T-axis (Fig. 10).

2.18.26. Tire nominal contact pressure (tire average contact pressure or tire average ground pressure)*

The tire static load or dynamic load divided by the tire contact area.

2.18.27. Tire radius*

One half of the tire diameter (see tire diameter).

2.18.28. Tire relaxation length**

The distance which a tire travels from the time point when the steering wheel is turned to the time point when the tire lateral force reaches 63% of its steady-state value (Cossalter, 2006).

2.18.29. Tire rolling circumference

See rolling circumference.

2.18.30. Tire rolling radius

See rolling radius.

2.18.31. Tire section height (unloaded tire section height)

The distance from the shoulder of the rim to the periphery of the tire, including tread, measured along the vertical center line of the cross section of the inflated but unloaded tire (Fig. 17; McRae et al., 1965).

2.18.32. Tire section height, loaded**

The minimum distance from the shoulder of the rim to the periphery of the tire, including tread, measured along the vertical center line of the cross section of the inflated and loaded tire.

2.18.33. Tire section width, loaded

The maximum outside width of the cross section of the loaded tire when the tire is resting on an unyielding, horizontal plane surface (Fig. 17; McRae et al., 1965).

2.18.34. Tire section width, unloaded

The maximum outside width of the cross section of the inflated but unloaded tire (Fig. 17; McRae et al., 1965).

2.18.35. Tire tread

Anything applied to the carcass surface (on the outer surface) intended to serve as a wearing surface and increase the traction or propulsion capacity of a vehicle.

2.18.36. Tire tread height

The perpendicular distance from the undertread face to the tread face, measured at the center line unless otherwise specified.

2.18.37. Tire unloaded radius (free radius)**

The radius of the tire-wheel assembly at a specified inflation pressure and zero normal load applied to the assembly, measured from the wheel axle centerline radially to the lowest point of contact area.

2.18.38. Toe angle**

The angle between a longitudinal axis of the vehicle (the X-axis in Fig. 6) and the line of intersection of the wheel plane and the road surface. The wheel is "toed-in" if the forward portion of the wheel is turned toward a central longitudinal axis of the vehicle, and "toed out" if turned away (Society of Automotive Engineers, 2008).

2.18.39. Torque radius**

The ratio of the input torque over the gross tractive effort (Zoz and Grisso, 2003), also referred to as the kinetic rolling radius in (Kiss, 2003).

2.18.40. Torque-slip curve

A plot of the torque delivered to the traction element vs the slip in a given soil condition (Tripartite Working Group on Ground Mobility, 1961).

2.18.41. Torque-stall

The failure of the delivered torque to the traction element to overcome total motion resistance. (During torque-stall the traction elements do not move.)

2.18.42. Towing mode**

The mode in which the vehicle, traction element, or transport element is moving at zero axle input torque (zero driving torque) and zero braking torque (Muro and O'Brien, 2004).

Towing mode is also referred to as pure rolling mode or free rolling mode in (Muro and O'Brien, 2004; Wong, 2008) and pulled mode in (Kutzbach et al., 2019).

2.18.43. Towing resistance*

The total motion resistance of a traction or transport element in the towing mode.

*2.18.44. Track average ground contact pressure***

The weight of the tracked vehicle divided by the ground contact area.

*2.18.45. Track contact width***

The overall width of an individual track excluding connecting links (Fig. 25; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

*2.18.46. Track cleat**

Normally the same as grouser. In (Asaf et al., 2006), cleat refers to a grouser with height greater than 11 mm.

*2.18.47. Track ground contact area**

The sum of the areas of the elements in direct contact with the ground. Includes interruptions due to openings within or between grousers (US army test and evaluation command, 1981).

*2.18.48. Track ground contact area, nominal**

The product of the nominal track ground contact length and the track ground contact width (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

*2.18.49. Track ground contact length**

The actual length of the tracks in contact with the ground (Fig. 26). Includes interruptions due to openings within or between grousers.

2.18.50. Track ground contact length, nominal

The length of track in contact with a flat, unyielding surface (Fig. 26).

*2.18.51. Track ground contact pressure**

The actual pressure exerted vertically on the ground surface (e.g., soil surface or non-deforming surface) by the track (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

*2.18.52. Track ground contact pressure, nominal**

The quotient obtained when the tracked vehicle gross weight is divided by the sum of the nominal ground contact areas of all tracks.

2.18.53. Track ground contact width

The maximum width of the contact elements, including connecting links (Fig. 25).

2.18.54. Track grouser

Same as grouser.

2.18.55. Track grouser height

The perpendicular distance measured from the track shoe face to the grouser face (Fig. 25; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.56. Track grouser pitch

Same as track grouser spacing (Fig. 27).

*2.18.57. Track grouser spacing (track grouser pitch)**

The distance between corresponding points on adjacent grousers when the track shoes are in the same plane (Fig. 27).

2.18.58. Track grouser width

The overall width of a grouser (Fig. 25; ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

*2.18.59. Track link***

A coupling element that connects adjacent track shoes by means of a hinged or flexible device (Fig. 27).

*2.18.60. Track link pitch**

The distance between center lines of adjacent track coupling elements when the track shoes are in the same plane (Fig. 27).

*2.18.61. Track pad (track plate)**

A replaceable traction surface element of a track shoe. A “Track Pad” is generally associated with a rubber traction surface that minimizes the surface damage on hard roads, whereas a “track plate” is generally associated with a steel traction surface (Fig. 27).

*2.18.62. Track pitch**

The distance between adjacent drive sprocket contact points when the track shoes are in the same plane (Fig. 27).

*2.18.63. Track plate**

Same as track pad, with the difference being “track plate” is generally associated with a steel traction surfaces and “Track Pad” is generally associated with a rubber traction surface.

2.18.64. Track shoe

The rigid track element that is connected by means of hinged or flexible devices to form the track (Fig. 25).

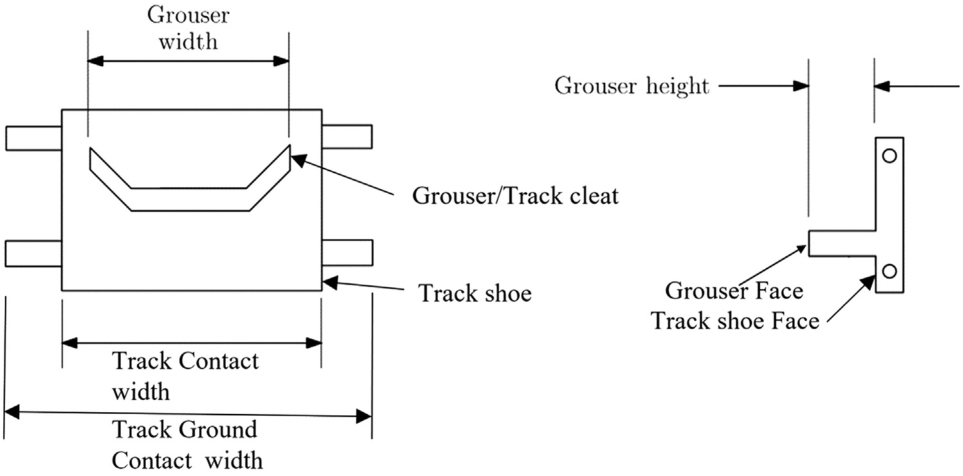


Fig. 25. Schematic of a track shoe with a grouser.

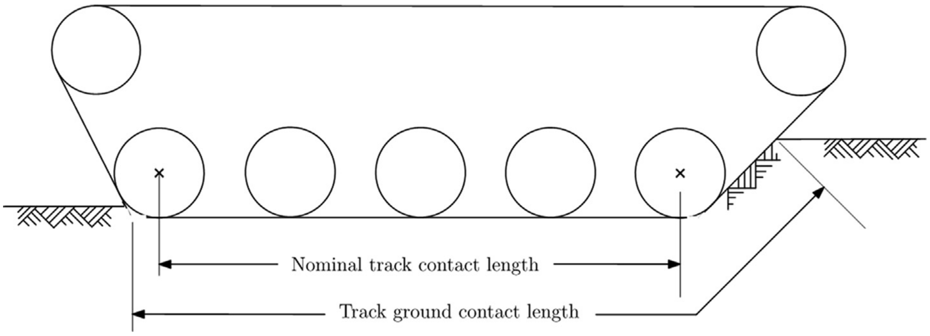


Fig. 26. Schematic of track on soft soil.

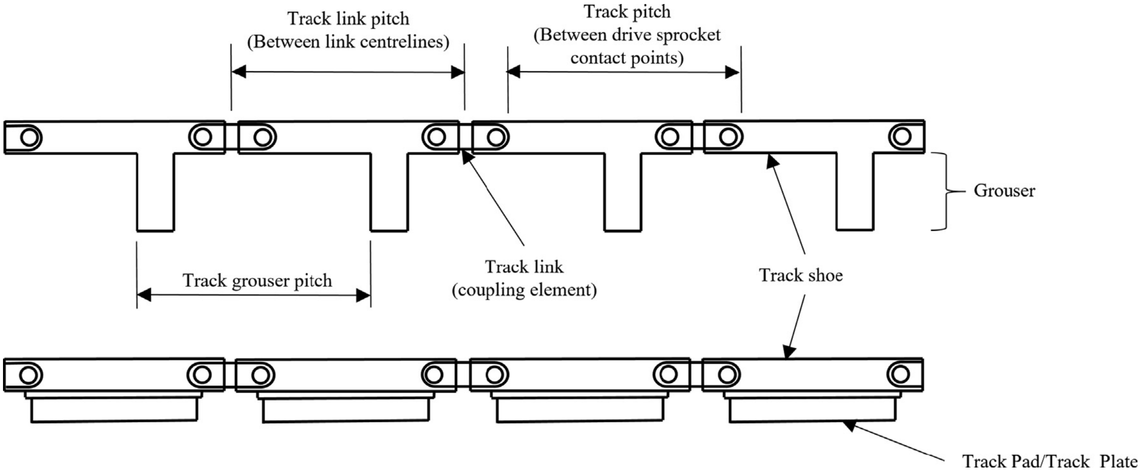


Fig. 27. Schematic illustrating different track pitch terms. This schematic portrays link tracks.

2.18.65. Track shoe face

The outermost surface of the track shoe, exclusive of grouser (Fig. 25).

*2.18.66. Track types**

i. *Link track.* A track built from modular metal, rigid track shoes which together compose a closed chain; the track shoes are joined by hinges or flexible devices. The link track comprising track shoes joined by hinges with dry pins (with rubber bushings for military vehicles) is also referred to as the segmented metal track or metal link track (Wong, 2009).
ii. *Band track (rubber endless track).* A track consisting of one or more bands either continuous (rubber belt tracks) or made up of shorter lengths joined together (segmented band tracks) and having a larger number of points of flexure than is required by the normal pitch of the sprocket (Tripartite Working Group on Ground Mobility, 1961). The band track formed around a basic carcass or belt, which mainly includes a belt-shaped rubber-like elastic member, is also referred to as the rubber belt track or rubber track.
iii. *Girderized track.* A track with links restrained from bowing due to the vertical soil reaction (Tripartite Working Group on Ground Mobility, 1961).
iv. *Live track.* A link track consisting of a connected series of links with an elastic medium in the joints so joined that some of the energy put into the joints during flexure is regained.
v. *Spaced-link track.* A track consisting of elements so designed that the grouser height to spacing ratio is intended to achieve general soil failure between the grousers.
vi. *Flexible track.* A link track having relatively short track pitch or a band track (Wong, 2009).

2.18.67. Tracked vehicle

A vehicle utilizing track or track-like traction and/or transport elements, exclusively.

*2.18.68. Traction**

Same as net tractive effort, if used alone or in the coefficient of traction. However, if used as an attributive word, e.g., gross traction or net traction, traction does not mean the net tractive effort.

*2.18.69. Traction, coefficient of (coefficient of net tractive effort, net traction coefficient, net traction ratio, or coefficient of net traction)**

The net tractive effort divided by the dynamic load applied on the traction element or the vehicle traction elements (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

*2.18.70. Traction element (traction device)**

Any element of a vehicle that is powered and designed to provide traction, by using reaction forces from a supporting surface, for a vehicle travelling on that surface (e.g. tires, wheels, tracks, feet, etc.).

2.18.71. Tractive efficiency**

See drawbar efficiency.

2.18.72. Tractive effort (tractive force or thrust)**

The force developed on the traction element-supporting surface interface (e.g., the tire-soil interface), acting parallel to the direction of travel, equal to the gross tractive effort minus the internal motion resistance; tractive effort could be also computed by the integration of the component of shear stress parallel to the direction of travel over the traction element-supporting surface interface (Lyasko, 2010b).

2.18.73. Tractive effort, gross, F_p (gross traction or gross tractive force)*

A pull force applied on the traction element, converted from the axle input torque, also referred to as rim pull, theoretical pull, or design drawbar pull (Zoz and Grisso, 2003). For a tire or wheel, the gross tractive effort is the axle torque (input torque) divided by the torque radius (Kiss, 2003; Zoz and Grisso, 2003; Tripartite Working Group on Ground Mobility, 1961).

2.18.74. Tractive effort, net, F_t, (traction, net traction, or net tractive force)*

The total force output of the traction element acting parallel to the direction of travel, i.e., the gross tractive effort minus the total motion resistance (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

For a traction element, the net tractive effort is the same as the drawbar pull (Wong, 2009).

2.18.75. Tractive effort coefficient (tractive effort ratio)**

The ratio of tractive effort to dynamic load applied on the traction element or the vehicle traction elements, also referred to as tractive coefficient (Lyasko, 2010b).

2.18.76. Tractive effort coefficient, gross (gross traction ratio, coefficient of gross tractive effort, gross traction coefficient, or coefficient of gross traction)**

The ratio of gross tractive effort to dynamic load applied on the traction element or the vehicle traction elements (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.77. Tractive effort coefficient, net**

See traction, coefficient of.

2.18.78. Traction mode**

See driving mode.

2.18.79. Trafficability

Same as terrain trafficability.

2.18.80. Transport element (transport device)*

Any element of a vehicle that is non-powered (zero input or output torque) and designed to provide support for a vehicle travelling on a surface (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.81. Travel reduction

Same as slip.

2.18.82. Tread radius**

The radius of curvature of the face of the lugs or tread measured at right angles to the center plane of the tire with the tire mounted on its recommended or approved rim after being inflated to the recommended pressure for 24 h, but without running time on the tire (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.18.83. Tread width

Same as tire contact width.

2.18.84. Trim height, suspension**

A vertical dimension that specifies the location of a point on a vehicle suspension relative to a point on the vehicle sprung mass (Society of Automotive Engineers, 2008).

2.18.85. Trim height, vehicle**

A vertical dimension that specifies the location of a fixed point on the vehicle body or chassis relative to the ground (Society of Automotive Engineers, 2008).

2.18.86. Turning radius (turn radius)*

The radius of the arc described by the center of the path made by the outside front wheel (or outside track) of a vehicle when making its shortest complete turn (U.S. Army Transportation Combat Developments Agency, 1962), or the radius of the arc described by the path made by the gravity center of a traction element (Pacejka, 2005) or vehicle (Wong, 2008).

2.19. U

2.19.1. Unconfined compressive strength, q_u*

The load per unit area at which an unconfined prismatic or cylindrical specimen of soil will fail in a simple compression test without lateral support (ASTM D653-14, 2014). (See unconfined compression test apparatus in Section 3 for the description of test equipment.)

2.19.2. Undertread face*

The outermost surface of the rubber traction element (on the carcass or track) where no lug or tread is located (ANSI/ASAE S296.5 DEC2003 (R2018), 2018).

2.19.3. Uniformity coefficient

Same as coefficient of uniformity.

2.19.4. Unit weight**

The density multiplied by standard gravitational acceleration of 9.806650 m/s^2 or a location-specific (local) value (ASTM D653-14, 2014).

2.20. Vxx

2.20.1. Vehicle*

A traction or transport machine used to transport a payload incorporating combinations of traction and/or transport elements.

2.20.2. Vehicle cone index, VCI

Minimum soil strength in the critical soil layer, in terms of rating cone index for fine grained soils or in cone index for coarse grained soils, required for a specific number of passes of a vehicle, usually one pass (VCI_1) or 50 passes (VCI_{50}) (Rula and Nuttall, 1971).

2.20.3. Vehicle environment

All environmental factors that affect the operation of a vehicle (Tripartite Working Group on Ground Mobility, 1961).

2.20.4. Vehicle height, overall

The distance from the contact plane to the uppermost point on the vehicle, including any protruding extremities (Wismer, 1965).

2.20.5. Vehicle height, reducible

The minimum height that can be achieved without major disassembly.

2.20.6. Vehicle length, overall

The maximum distance from the front to rear of a vehicle, including any protruding extremities (Wismer, 1965).

2.20.7. Vehicle length, reducible

The minimum length that can be achieved without major disassembly.

2.20.8. Vehicle mobility

Same as mobility.

2.20.9. Vehicle wheel track (track width)

The lateral distance between the contact centers of a pair of tires on an axle, measured parallel to the Y axis, with the vehicle at rest on a horizontal surface, at a prescribed load condition, set of vehicle trim heights, or set of suspension trim heights. For vehicles with dual wheels it is the distance between the points centrally located between the contact centers of the inner and outer dual tires (Society of Automotive Engineers, 2008). For a tracked vehicle it is the distance between the centers of the tracks.

2.20.10. Viscoelasticity**

Property of a material that strains under stress partly elastically and partly viscously, that is, whose strain is partly dependent on time and magnitude of stress (ASTM D653-14, 2014).

2.20.11. Viscoplasticity**

Property of a material whose strain is irreversible (inelastic) and dependent on time (Lemaitre, 2001).

2.20.12. Viscosity**

The internal fluid resistance of a substance which makes it resist a tendency to flow (ASTM D653-14, 2014).

2.20.13. Void ratio, *e*

The ratio of the volume of void space to the volume of solid particles in a given soil mass, V_s; that is

$$e = (V_a + V_w)/V_s \tag{23}$$

where e is void ratio. (Fig. 11; ASTM D653-14, 2014).

2.21. W

2.21.1. Water content (moisture content), gravimetric, w_g*

The ratio, expressed as a percentage, of the weight of water in a given soil mass, W_w, to the weight of solid particles, W_s; that is

$$w_g = \frac{W_w}{W_s} \times 100 \tag{24}$$

where w_g is gravimetric water content (Fig. 11; ASTM D653-14, 2014).

For the standard measurement methods of gravimetric water content, see (ASTM D2216-19, 2019; ASTM D4643-17, 2017; ASTM D4959-16, 2016; ASTM D7698-19, 2019; ASTM D6938-17a, 2017; ASTM D4944-18, 2018; ASTM D6780/D6780M-19, 2019; ASTM D7830/D7830M-14, 2014; ISO 11465:1993, 1993; ISO 17892-1:2014, 2014).

2.21.2. Water content, volumetric, w_v**

The volume of water present, V_w, in the unit volume of soil, V (Fig. 11; Gardner, 1986); that is

$$w_v = \frac{V_w}{V} \times 100 \tag{25}$$

where w_v is volumetric water content.

2.21.3. Water performance

The ability of a floatable vehicle to operate in water.

2.21.4. Weight, base vehicle**

The total weight of the vehicle, including all fluids necessary for normal operation, without fuel and without a payload (Society of Automotive Engineers, 2008).

2.21.5. Weight, curb

The weight of a fully equipped vehicle in operating condition with full fuel load, lubricants, and water (when required), but without crew or payload unless otherwise specified (U.S. Army Transportation Combat Developments Agency, 1962; Society of Automotive Engineers, 2008).

2.21.6. Weight, gross, *W*

The total weight of a vehicle, including payload.

2.21.7. Weight, payload

The weight of cargo and/or passengers, including crew, imposed on vehicle.

2.21.8. Weight, sprung*

All weight that is supported by the suspension, including portions of the weight of the suspension members. The sprung weight is the vehicle operating weight less the unsprung weight (Society of Automotive Engineers, 2008).

2.21.9. Weight, unsprung*

All weight that is not carried by the suspension, but is supported directly by the tires. The unsprung weight includes the weight of the tires and wheels and all parts that move directly with the tires and wheels, plus a portion of the weight of the suspension linkages, ride springs, and driveshafts (Society of Automotive Engineers, 2008).

2.21.10. Weight, vehicle operating**

The total weight of the vehicle at a given load condition, including the base vehicle weight, the weight of the fuel load, and the payload (Society of Automotive Engineers, 2008).

2.21.11. Weight-payload ratio

The curb weight of a vehicle divided by its payload.

2.21.12. Weight transfer (load transfer)*

The change in load (namely the normal force, normal to the supporting surface) on the traction and transport elements of a vehicle under specified operating conditions when compared to the static vehicle on level ground.

The weight transfer can happen because of (1) internal vehicle forces, the change in weight between axles due to inertia and changes in the line of action of gravity from centers of mass as the angle of slope changes and (2) external forces applied to a vehicle, particularly through hitches and linkages: a ground engaging implement generates horizontal and vertical forces (weight addition) on an agricultural tractor through a real or virtual hitch point, usually increasing the weight on the drive wheels or track.

2.21.13. Wet density (wet bulk density), γ_w*

The weight of solids and water, *W*, per unit of total volume of soil mass, *V*, irrespective of the degree of saturation; that is

$$\gamma_w = W/V \tag{26}$$

where γ_w is wet density (Fig. 11; ASTM D653-14, 2014).

For the standard measurement methods of wet density, see (ASTM D7263-09(2018)e2, 2018; ASTM D1556/D1556M-15e1, 2015; ASTM D2167-15, 2015; ASTM D2937-17e2, 2017; ASTM D4914/D4914M-16, 2016; ASTM D5030/D5030M−13a, 2013; ASTM D6780/D6780M-19, 2019; ASTM D6938-17a, 2017; ASTM D7698-19, 2019; ASTM D7830/D7830M-14, 2014; ISO 11272:2017, 2017; ISO 17892-2:2014, 2014).

2.21.14. Wet unit weight*

Wet density multiplied by standard acceleration of gravity (ASTM D653-14, 2014).

2.21.15. Wheel mobility number coefficient**

A dimensionless variable that is an empirical function of tire load and tire geometrical parameters, used in the expression of wheel mobility numbers (Taheri et al., 2015; Hegazy and Sandu, 2013). See wheel mobility number.

2.21.16. Wheelbase

The distance between the front and rear axles of a two axle vehicle.

2.21.17. Wheeled vehicle

A vehicle utilizing wheel or wheel-like traction and/or transport elements exclusively. Wheeled vehicles may be categorized by the expression $m \times n$, where m is the number of wheels and n is the number of powered wheels (here dual wheels are considered one wheel); e.g. a common automobile is a 4 × 2, an SUV is usually 4 × 4 or 6 × 6 (the Pinzgauer), tractors are usually 4 × 2 or 4 × 4, and military multi-axle vehicles can be 8 × 8 or more.

2.22. Y

2.22.1. Yaw

Same as angle of yaw.

2.23. Z

2.23.1. Zero condition**

The condition used to specify rolling radius. Four possible conditions are common (ANSI/ASAE S296.5 DEC2003 (R2018), 2018):

1. A self-propelled condition on a non-deforming surface (recommended for rolling circumference data).
2. A self-propelled condition on the test surface.
3. A towed condition, i.e., the vehicle or traction element is in towing mode, on a non-deforming surface.
4. A towed condition, i.e., the vehicle or traction element is in towing mode, on the test surface.

3. Terrain-test devices associated with terrain-vehicle tests

3.1. Aerial cone penetrometer*

A projectile with a cone-shaped striking point (an inertial cone penetrometer) that can be dropped from an airplane or fired from the ground by a mortar or similar gun (Fig. 28). By telemetry or ejection of a flare, a signal is sent to the operator to indicate the depth of penetration or the deceleration experienced by the penetrometer upon striking the soil. This information is related to the cone index, remolding index, and rating cone index of the soil and can be interpreted in those terms (Blackmon et al., 1963). Two types of aerial cone penetrometer were developed in (Mobility and Environmental Systems Laboratory (U.S.), 1958), a laboratory model and a field model; the laboratory model had 774.4 mm (30.5 in.) over-all length, 539.8 g (1.19 lb.) gross weight, and 1141.9 mm^2 (1.77 in.^{2}) cross-sectional area; the field model was 914.4 mm (36 in.) long and weighed 539.8 g (1.19 lb.).

3.2. Airfield penetrometer*

A cone penetrometer used to measure the trafficability of landing sites for aircraft (Fig. 29). It consists of a 30° cone with a 129 mm^2 (0.20 in.^{2}) base area. On the opposite end of the shaft are a spring, a load indicator, and a handle (Fenwick, 1965). The force required to move the cone through a layer of soil is named airfield index (AI) of that layer. AI is read from the load indicator (Grau, 1981).

3.3. Bevameter*

An instrument used to measure the in situ soil parameters associated with the shear stress-shear displacement (shear deformation) and pressure-sinkage relationships. The instrument normally consists of two separate devices: the shear test device to measure the shear stress and shear displacement and the sinkage test device to measure the pressure and sinkage. The bevameter is associated with the following parameters:

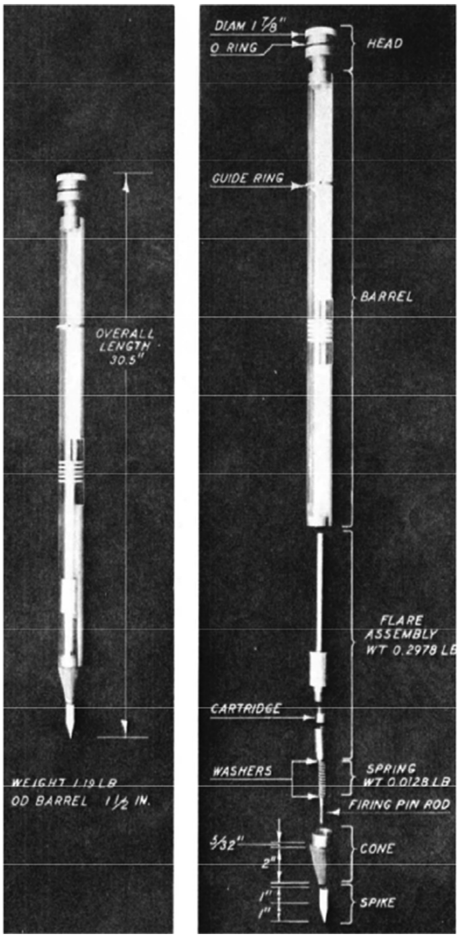


Fig. 28. Laboratory model of an aerial cone penetrometer. Reprinted from (Mobility and Environmental Systems Laboratory (U.S.), 1958) with permission of US Army Engineer Research & Development Center.

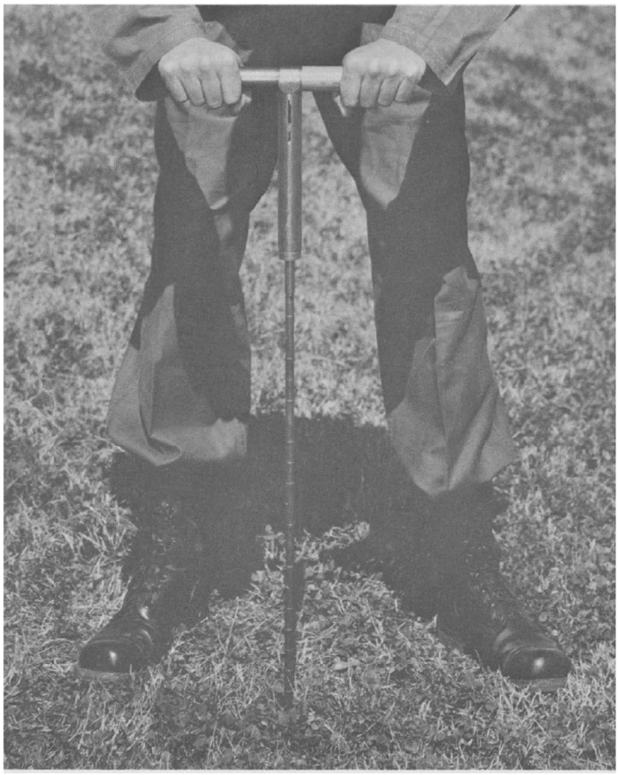


Fig. 29. Airfield penetrometer in use. Reprinted from (Burns and Carr, 1965) with permission of US Army Engineer Research & Development Center.

i. cohesion, c_b
ii. angle of internal friction, φ_b
iii. sinkage moduli, e.g., the ones in the Bekker's pressure sinkage equation, k, k_c, k_φ, and
iv. sinkage exponent, n.

The shear test device consists of an annular ring with grousers mounted on the end of a shaft (Fig. 30). In the shear tests, a number of constant vertical loads are applied to the ring which is then rotated at a constant velocity; the torque to rotate the ring and angular displacement of the ring are recorded and used to calculate the soil parameters related to the shear stress-shear displacement relationship.

The sinkage test device mainly consists of a plate penetrometer with circular, rectangular or elliptical plates (Fig. 31). In the sinkage tests, different sizes of flat plates are forced into the soil. The penetration force and sinkage are continuously recorded and used to calculate the soil parameters related to the pressure-sinkage relationship (Society of Automotive Engineers, 1967b).

3.4. California Bearing Ratio (CBR) equipment*

Equipment used to measure the shear strength and bearing capacity of soil in the field or on compacted samples in the laboratory. The equipment used mainly for testing soil in the laboratory consists of (ASTM D1883-16, 2016; United States Department of the Army, 2001):

1. a mechanical screw jack or a loading machine for applying load to a penetration piston,
2. a load-indicating device,
3. a penetration depth measuring device,
4. a circular penetrating piston 1934.5 mm^2 (2.998 in.^{2}) area and 102 mm (4 in.) high,
5. a swell (in height) measurement device,
6. expansion-measuring apparatus,
7. surcharge weights,
8. a CBR mold,
9. a spacer disk around 63.5 mm (2.5 in.) high,
10. and a compaction tamper (rammer).

The equipment used mainly for field CBR testing is a dynamic cone penetrometer (United States Department of the Army, 2001; ASTM D6951/D6951M-18, 2018).

Fig. 30. Shear test device of a portable bevameter. Reprinted from (Rula and Nuttall, 1971) with permission of US Army Engineer Research & Development Center.

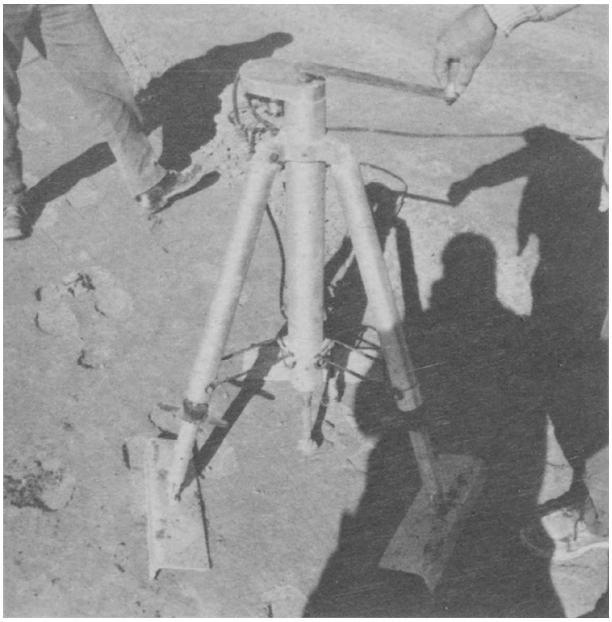


Fig. 31. Sinkage test device of a portable bevameter. Reprinted from (Rula and Nuttall, 1971) with permission of US Army Engineer Research & Development Center.

3.5. Cohron sheargraph*

A device used to measure the in situ soil shear strength. It consists of a torsional shear head attached to a recording drum by means of a spiral spring (Fig. 32). Normal and shear forces are transmitted to the shear head via a spring; the compression and rotation of the spring is recorded on graph paper attached to the upper part of this device (Kirby et al., 1994). By applying a combination of axial–torsional load a shear stress-normal stress curve is produced. Repeated tests at different loads will trace an envelope of curves which may be used to calculate the soil cohesion, c_c, and angle of internal friction, φ_c (Cohron, 1963).

3.6. Canadian hardness gage

An instrument for measuring the strength of a snow surface. It consists of a spring-loaded plunger on which may be mounted various-sized disks. The disk is pressed against the snow and the load recorded when a definite collapse of the snow surface is observed (U.S. Army Engineer Waterways Experiment Station, 1960).

3.7. Cone penetrometer**

A penetrometer of which the leading point of the penetrometer tip is a conical point (ASTM D3441-16, 2016), the apex angle of the cone is typically 30°, 45°, or 60°. Cone penetrometers can be divided into 6 types: (1) static, (2) quasi-static, (3) dynamic, (4) quasi-static & dynamic, (5) screw, and (6) inertial (Schertmann, 1977; Perumpral, 1987). The cone penetrometer is associated with the following parameters:

i. cone index (CI)
ii. remolding index (RI)
iii. rating cone index (RCI)
iv. vehicle cone index (VCI)
v. critical layer

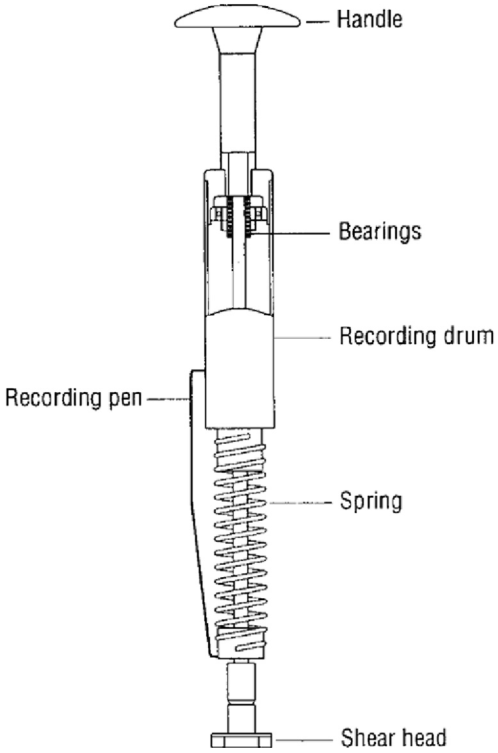


Fig. 32. Schematic of a Cohron sheargraph. Reprinted from (Kirby et al., 1994) with permission of Elsevier.

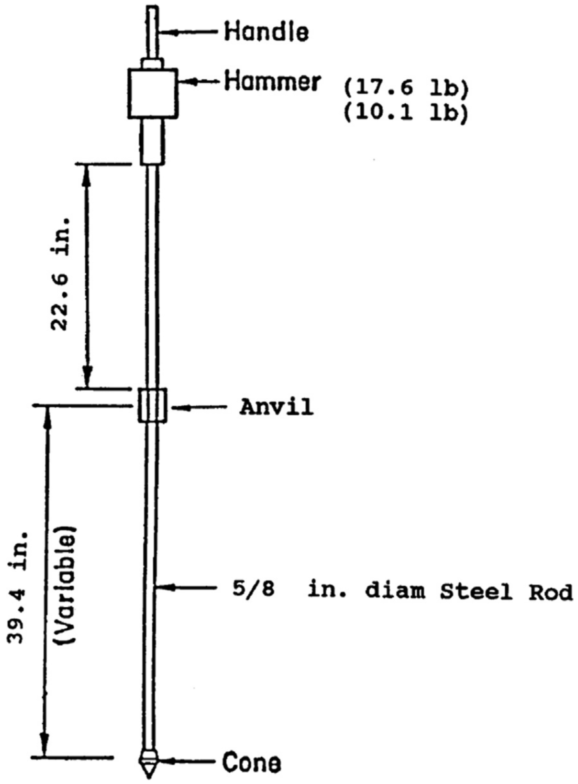


Fig. 33. The schematic of a dynamic cone penetrometer. The drop weight is a hammer, the impact between the hammer and the anvil forces the dynamic cone penetrometer into the soil. Reprinted from (Webster et al., 1992) with permission of US Army Engineer Research & Development Center.

3.8. Cone penetrometer, dynamic**

A type of cone penetrometer that includes a drop weight and a guide rod (Fig. 33); it is pushed into the soil by the impact of the drop weight (Perumpral, 1987). The drop weight is raised to a certain height on the guide rod and then dropped free along the guide rod. The penetration per impact of the drop weight cannot be seen as a quasi-static process. The dynamic cone penetrometer records not the penetration resistance but the penetration depth per impact of the drop weight. Formulas have been proposed to convert the penetration depth per impact to the penetration resistance (Vaz and Hopmans, 2001).

For the standards for using dynamic cone penetrometers, see (ASTM D7380-15, 2015; ASTM D6951/D6951M–18, 2018)

3.9. Cone penetrometer, static or quasi-static**

A type of cone penetrometer that is pushed into soil manually or by the mechanical, hydraulic, or electric power (Perumpral, 1987). The penetration can be considered a continuous and quasi-static process. Schmertmann (1977) categorized those with extremely slow penetration rate as the static cone penetrometer and those with 10–20 mm/s penetration rate as the quasi-static cone penetrometer. Static or quasi-static cone penetrometers can usually measure penetration resistance (force or pressure), and some of them nowadays can also record multiple measurements of penetration resistance and penetration depth and give an indication of the penetration speed (Kees, 2005).

Fig. 34. A WES cone penetrometer in use. A dial indicator displays the reading of the penetration resistance. Reprinted from (Mobility and Environmental Systems Laboratory (U.S.), 1957) with permission of US Army Engineer Research & Development Center.

For the standard for static cone penetrometers, see (ASAE S313.3 FEB1999 (R2018), 2018).

*3.10. Cone penetrometer, Waterways Experiment Station (WES)**

A static penetrometer first designed by Waterways Experiment Station (named after it) and used to obtain an index of in situ shear strength of soil (Fig. 34). It consists of a 30° cone with a 323 mm^2 or 129 mm^2 (0.5 in.^{2} or 0.2 in.^{2}) base area mounted on one end of a driving shaft. The shaft has circumferential bands to indicate depths of penetration. At the top of the shaft is mounted a dial indicator within a proving ring which indicates the force applied axially to the penetrometer. The instrument is forced vertically into the soil while records are made of the dial reading for various penetration depths (Society of Automotive Engineers, 1967b; United States Department of the Army and the Air Force, 1968).

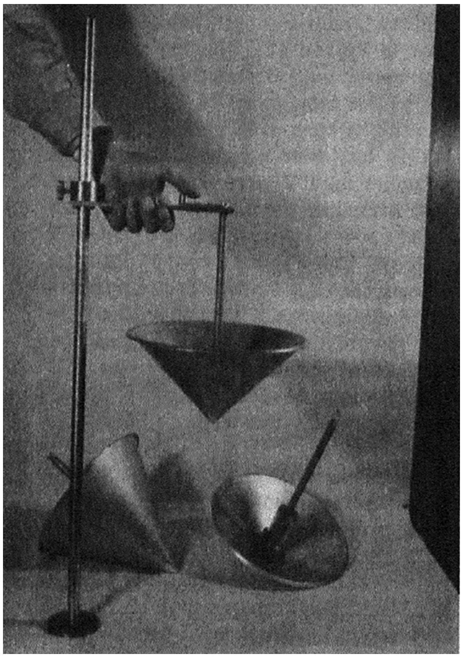


Fig. 36. Snow drop cone penetrometer. Reprinted from (Bader et al., 1951) with permission of U.S. Army Cold Regions Research and Engineering Laboratory.

*3.11. Direct shear device**

A device used to measure soil shear strength under drained or undrained conditions (Fig. 35). It mainly consists of a device to hold a soil specimen securely between two porous stones in such a way that torque cannot be applied to the specimen. The device provides a means for applying a normal stress to the faces of the specimen, for measuring change in thickness of the specimen, for permitting drainage of water through the porous stones, and for submerging the specimen in water. The device is capable of applying a shearing force to shear the specimen along a predetermined shear plane (single shear) or shear planes (double shear) parallel to the faces of the specimen (ASTM D3080/D3080M-11, 2011; US Army Corps of Engineers, 1970). The shear test using the direct shear device is associated with the following parameters:

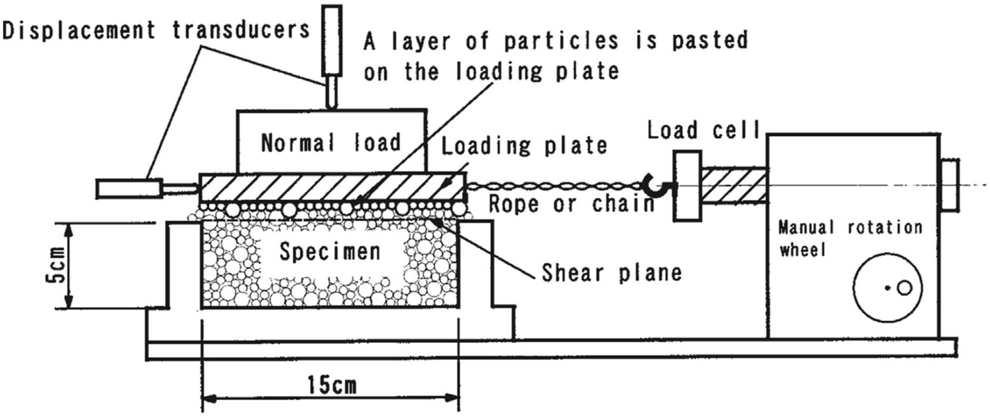


Fig. 35. Schematic of a direct shear device. Reprinted from (Matsuoka et al., 2001) with permission of ASTM International.

i. cohesion, c_d
ii. angle of internal friction, φ_d

For the standard test methods for direct shear tests, see (ASTM D3080/D3080M-11, 2011; ASTM D6528-17, 2017; ISO 17892-10:2018, 2018; AASHTO T 236, 2018).

*3.12. Drop-cone penetrometer, snow**

An instrument used to determine the strength of snow (Fig. 36). It consists of a sheet-aluminum 60° cone weighing 0.5 kg and having a central spindle, a graduated support rod 0.8 m long mounted on a flat base, and a movable, horizontal arm equipped with a bubble level. A trip lever to release the penetrometer is fitted to the spindle. Weights of 0.5 kg, 1.0 kg and 2.0 kg are provided to load the penetrometer. In operation the movable arm is set at a preselected height on the support rod. The appropriate weight is then placed on the cone spindle and the cone dropped by releasing the trip lever. The graduated support and movable arm are then used to measure the depth of penetration of the cone into the snow (U.S. Army Engineer Waterways Experiment Station, 1960).

*3.13. Oakfield punch**

A device used to obtain small disturbed soil samples. It is a tube with a cutting edge at one end and a handle attached to the other. A considerable length of sidewall is removed along the length of the tube between the cutting edge and the handle. Depth indexes are inscribed on the tube. The tube is pushed into the soil till the first 76.2-mm (3-inch) mark, the handle is turned to break the soil column, and the punch is then withdrawn from the soil. The soil may then be easily removed from the tube by pushing with the fingers through the cut-out in the side wall. After placing the soil in a covered soil can, the punch is inserted again in the same hole till the 152.4-mm (6-inch) mark and soil is removed. More soil samples are extracted in increments of 76.2 mm (3 in.). Successive soil samples from other depths may be obtained in a like manner (U.S. Army Engineer Waterways Experiment Station, 1962).

*3.14. Penetrometer***

A tool used for penetrating soil that mainly consists of a series of driving shafts and a penetrative terminal body, which is called the penetrometer tip (ASTM D3441-16, 2016).

*3.15. Penetration-shear device, combined**

A device used to measure in situ soil strength. Various designs exist; however, all apply a vertical load and a horizontal load or torque at the same time. Records of these loads and their associated sinkages are used to describe soil strength. An example of the combined penetration-shear device is the vane cone.

*3.16. Proctor needle (penetrometer needle)**

A penetrometer used to measure the penetration resistance of a compacted soil sample. The penetration resistance, wet unit weight, and moisture content are used to estimate the degree of compaction. The entire instrument consists of a handle and calibrated plunger rod on one end, a barrel with a piston resting on a spring in the middle section, and one of several sized needles, ranging in an area from 16 to 645 mm^2 (0.025–1.00 $in.^2$) on the other end. The needle is forced into the soil at a rate of approximately 12.7 mm (1/2 in.) per sec to a depth not less than 76.2 mm (3 in.) and the maximum resistance is measured (ASTM D1558-10, 2010; Johnson and Sallberg, 1960).

*3.17. Rammsonde penetrometer**

A dynamic cone penetrometer used to determine the relative strength of snow layers to depths of several meters. The standard Rammsonde penetrometer includes several hollow, 20 mm diameter shafts and a drop hammer, 1 kg, 2 kg, or 3 kg in weight. The end of one of the shafts is a 60° cone with 40 mm diameter and 35 mm conical height, as shown by Fig. 37. The base of the cone is tapered back to the shaft. The total height of the penetrometer tip is 100 mm. The drop hammer moving along a guide shaft forces the cone into the snow (U.S. Army Engineer Waterways Experiment Station, 1960; Niedringhaus, 1965; Ueda et al., 1975).

*3.18. Remolding equipment**

In conjunction with the cone penetrometer this equipment is used to measure the remolding index (RI) of soil or the soil strength change experienced during remolding. The remolding equipment (Fig. 38) consists of a cylinder (the remold cylinder) and a drop hammer. The remold cylinder, mounted on a steel base, is of the same diameter as the Hvorslev sampler. The drop hammer weighs 1.13 kg (2.5 lb.) and travels 305 mm (12 in.). Samples of soil are inserted into the remold cylinder from the Hvorslev sampler. For fine-grained soils the drop hammer is allowed to fall on the soil sample within the remold cylinder 100 times; for coarse-grained soils with fines the remold cylinder with the soil is dropped from a height of 152 mm (6 in.) on to a firm surface 25 times. After this procedure the change of soil strength is measured by a cone penetrometer (Mobility and Environmental Systems Laboratory (U. S.), 1958; Meyer and Knight, 1961; Society of Automotive Engineers, 1967b; United States Department of the Army and the Air Force, 1968).

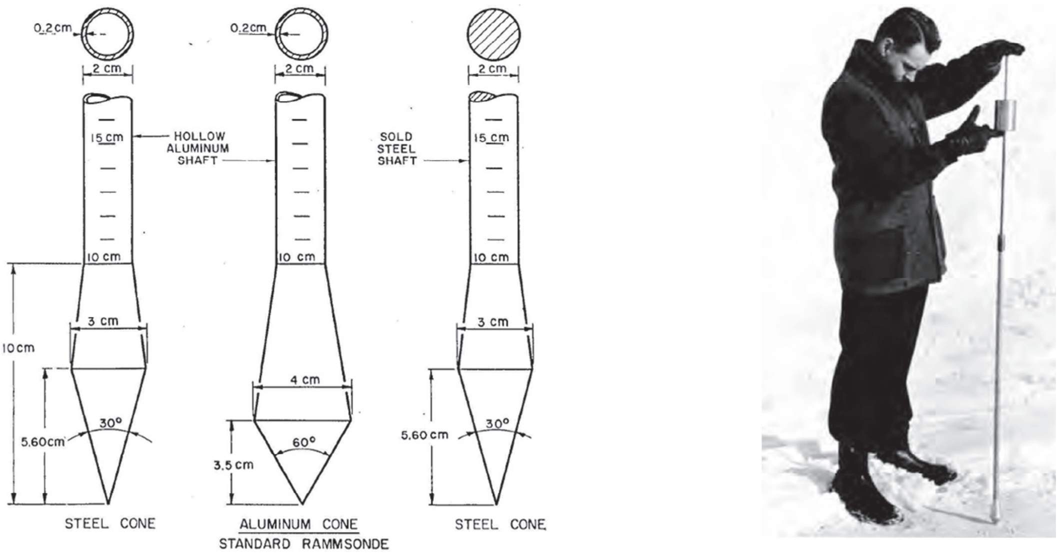
*3.19. Sampler***

A device that mainly consists of a tube with circular (core sampler), rectangular, or complex-shape cross section, used to sample soil from the spot of interest. For the measurement of strength, compressibility, permeability, and density that requires intact soil, the samplers utilized are designed and operated in a way that the soil to be extracted is disturbed as little as possible during sampling. For the soil classification testing, the samplers utilized can be equipped with augers to advance the hole and bring up disturbed soil samples.

For the standards for choosing and using the proper samplers, see (ASTM D1452/D1452M-16, 2016; ASTM D1587/D1587M-15, 2015; ASTM D2937-17e2, 2017; ASTM D4700-15, 2015; ASTM D2944-14, 2014). The standards more relevant to geotechnical engineering, targeting at the deep soil that hardly influences vehicle mobility, are not listed here.

*3.20. Sampler, Hvorslev**

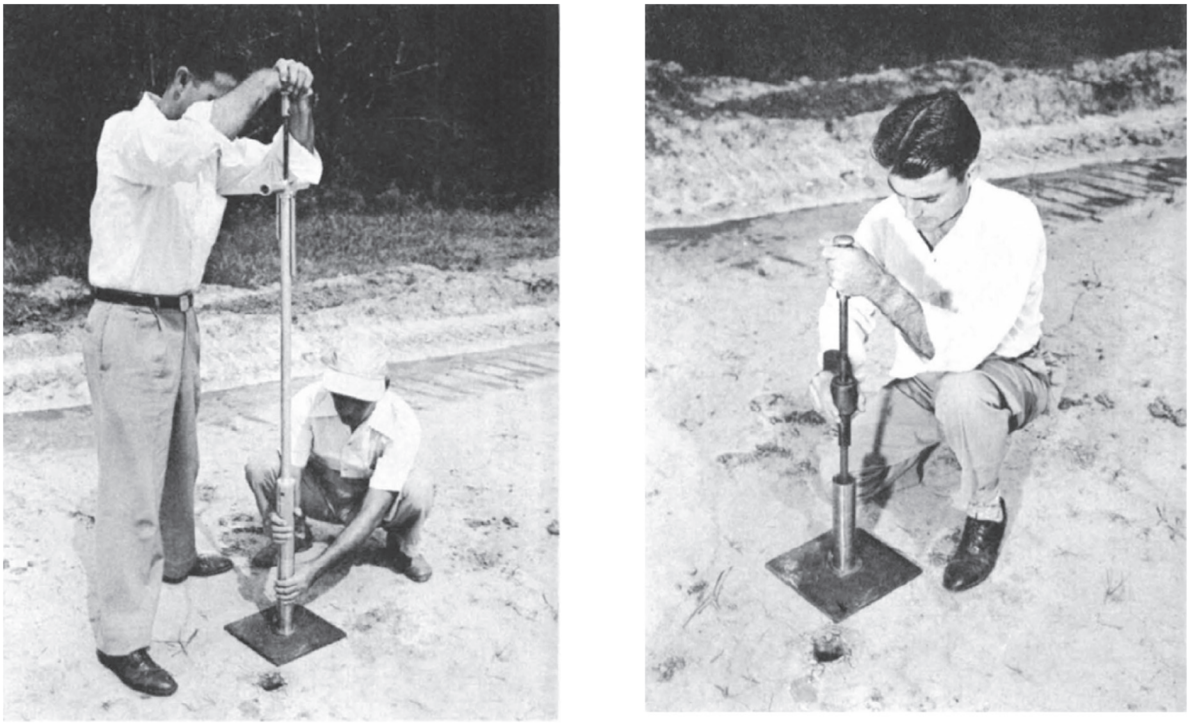
A device used to obtain an undisturbed sample from comparatively soft soil (Fig. 39). It consists of a tube, with around 47.625 mm (1–7/8 in.) i.d. and 87.706 mm (3.453 in.) length, externally sharpened on one end. A piston within the tube is retracted during penetration in order to maintain a partial vacuum above the soil and thus to prevent soil compression as the cylinder is forced into the soil. The piston also prevents moisture loss by drainage in non-cohesive soils. It is primarily used to obtain soil samples for use in the remolding test or for determination of moisture-density (United States Department of the Army and the Air Force, 1968; Stevens et al., 2013).



(a) Rammsonde cones. Reprinted from (Niedringhaus, 1965) with permission of U.S. Army Cold Regions Research and Engineering Laboratory.

(b) Rammsonde penetrometer in use. Reprinted from (Ueda et al., 1975) with permission of U.S. Army Cold Regions Research and Engineering Laboratory.

Fig. 37. Rammsonde cone penetrometer.



(a) Soil is transported from the Hvorslev sampler to the remold cylinder.

(b) Drop hammer is blowing the soil in the remold cylinder.

Fig. 38. Remolding equipment in use. Reprinted from (Mobility and Environmental Systems Laboratory (U.S.) (1958)) with permission of US Army Engineer Research & Development Center.

Fig. 39. Hvorslev soil sampler. Reprinted from (Stevens et al., 2013) with permission of US Army Engineer Research & Development Center.

3.21. Sampler, peat*

A sampler used to obtain undisturbed samples of unfrozen peat. The sampler (corer) mainly consists of a tube, open at one end, with a sharp cutting edge, drawing in the peat through penetration. The tube could be cylindrical (van Asselen and Roosendaal, 2009), rectangular (Seaby, 2001), or of complex shape, e.g., the "Russian" sampler (Pitkänen et al., 2011). The sampler may contain liners which fit the inner surface of the sampler perfectly and collect the peat sample (van Asselen and Roosendaal, 2009), or a piston capable of providing the suction of peat sample, normally connected to a rod or wire to facilitate the piston movement (Landva et al., 1983). Extension rods are attached to the tube to facilitate the penetration and retraction of the tube. Typical types of peat samplers are "Russian sampler", piston sampler, and "Hiller sampler" (van Asselen and Roosendaal, 2009).

3.22. Sampler, San Dimas*

A device used to obtain sample cores [69.1 mm (2.72 in.) diameter by 50.8 mm (2 in.) or 76.2 mm (3 in.) length] for the determination of bulk density. The sampler has an outer cylinder equipped with spiral flanges with sharp cutting edges and an inner cylinder with three removable brass sleeves. The largest sleeve is the size of the desired core. When the handle attached to the outer cylinder is rotated clockwise, the flanges cut the soil around the outer cylinder and convey it upward and away from the sampling tube. The inner cylinder does not rotate but moves downward into the soil. The design permits the inner cylinders to penetrate undisturbed soil (U.S. Army Engineer Waterways Experiment Station, 1954; Andrews and Broadfoot, 1958).

3.23. Shear annulus (annular shear ring)**

An annular plate that can have either a metal or rubber surface as well as grousers distributed radially (Figs. 30 and 40). The shear annulus is a part of the Bevameter and used in the shear test (Shoop, 1993).

3.24. Shear plate, grouser**

A plate that has grousers distributed in parallel and moves across the soil in a linear mode in the shear test (Figs. 40 and 41; Shoop, 1993).

3.25. Shear vane*

An instrument used to measure the in situ shear strength of soil at a specified depth (Fig. 42). Although a number of shaft and vane sizes have been used, most devices consist of a cruciform vane mounted on one end of a shaft. On the other end is a device to measure the torque required to rotate the shaft about its axis (ASTM D2573/D2573M-18, 2018).

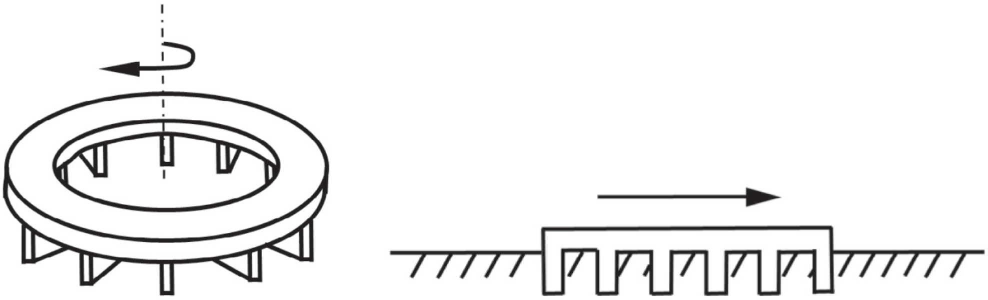
For the standard test methods for shear tests using a shear vane, see (ASTM D2573/D2573M-18, 2018; ASTM D4648/D4648M-16, 2016; ASTM D8121/D8121M-18, 2018).

3.26. Single wheel tester**

A type of test facilities that tests the tractive, braking, and/or steering performance of a tire or wheel on soil or road in laboratory or field. An example is given in Fig. 43. The single wheel tester features one actuation module to power tire longitudinal motion or tire rotation or two actuation modules to power the tire longitudinal motion and tire rotation separately. A trailer or carriage (where the tire is mounted) with a vehicle or power transmission system towing the trailer or carriage is a common design. Another design is the instrumented vehicle, such as the Saab friction tester and the CRREL instrumented vehicle. The instrumentation of single wheel testers enables the measurement of parameters among net tractive effort, driving/braking torque, lateral force, slip ratio, tire/wheel sinkage, etc. The configuration of single wheel testers allows controlling tire/wheel normal load, slip ratio, and/or inflation pressure, or setting slip angle or steering angle. The laboratory single wheel tester is equipped with a soil bin that provides better control of soil condition. (Shoop et al., 1994; Kutzbach et al., 2009; He et al., 2017)

3.27. Soil density measuring devices*

i. Gravimetric samplers. A number of samplers are designed to extract a known volume of undisturbed soil, e.g., Hvorslev sampler, peat sampler, and San Dimas sampler. These may be used directly to measure in situ soil density (ASTM D2937-17e2, 2017; ASTM D4700-15, 2015; ASTM D7263-09(2018)e2, 2018).
ii. Nuclear density devices (ASTM D6938-17a, 2017).
   1. Back scatter method. Density values are obtained by measuring the nuclear radiation, reflected by the soil, which has been emitted from a known source. The rate of radiation reflected is proportional to the density of the soil.
   2. Direct transmission method. Density values are obtained by measuring the radiation received by a detector which is placed in the soil adjacent to a radiation source. The rate of radiation received by the detector is inversely proportional to the soil density.



(a) *Shear annulus.* (b) *Grouser shear plate.*

Fig. 40. Schematics of shear plates.

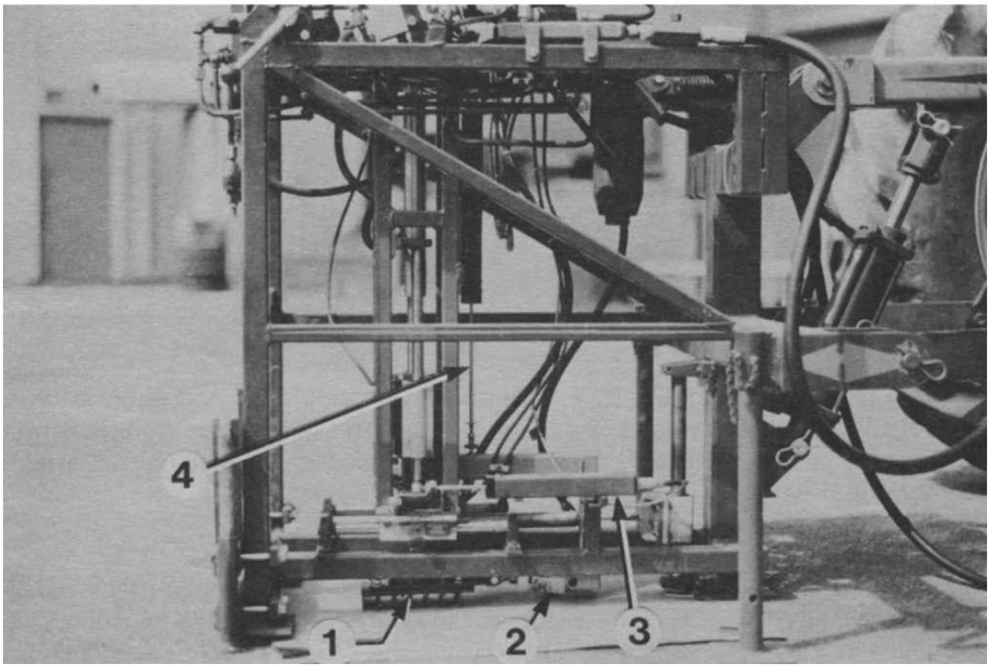


Fig. 41. Grouser plate attached to the test device developed by Upadhyaya et al (Upadhyaya et al., 1993). Reprinted from (Upadhyaya et al., 1993) with permission of Elsevier.

iii. Sand cone apparatus*. A device, consisting of a sand container, sand cone, and base plate, which is used to measure in situ soil density. A sand is calibrated to determine the volume it occupies per unit weight when poured by a specific technique. A sample is extracted from a level portion of the soil and weighed. The calibrated sand is then poured into the void until the surface is again level. The weight of sand will yield the volume of soil extracted (ASTM D1556/D1556M-15e1, 2015).

iv. Electrical probe**. The complex-impedance method specifies the use of electrical probes which are fixed vertically in the soil. A radio frequency voltage is applied to them to determine electrical properties of the soil which are further used for determining density. (ASTM D7698-19, 2019)

v. Electromagnetic impedance spectroscopy device**. The device that measures the electromagnetic properties of the soil as a function of frequency; this function is compared with an empirical model and other calibration checks to determine the wet density (ASTM D7830/D7830M-14, 2014).

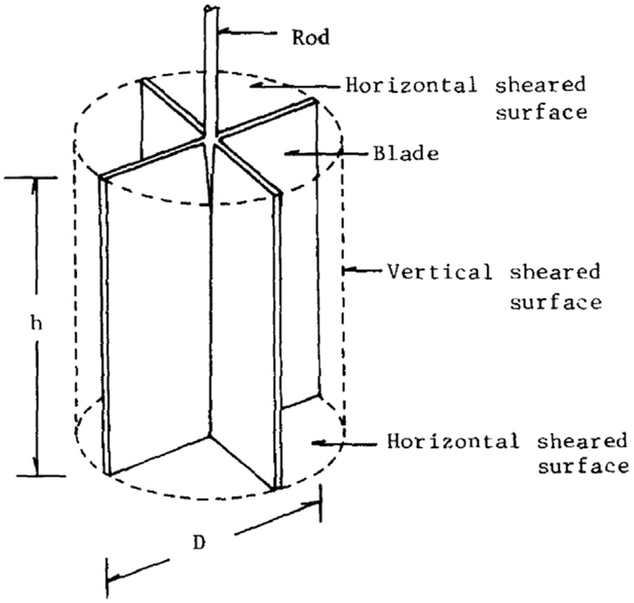


Fig. 42. Schematic of a shear vane. Reprinted from (K. Kogure, H. Yamaguchi, 1988) with permission of Elsevier.

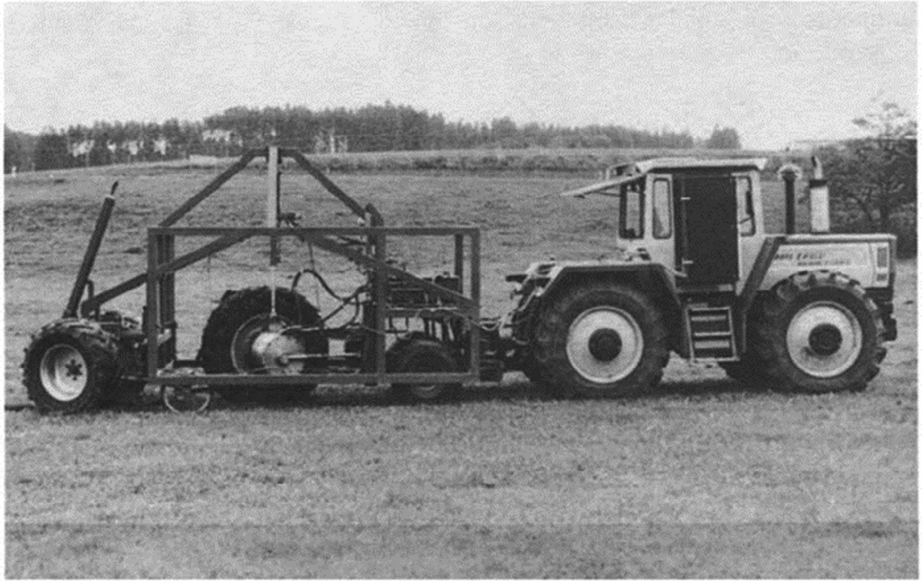


Fig. 43. A single wheel tester at Hohenheim University. Reprinted from (Armbruster and Kutzbach, 1991) with permission of Elsevier.

*3.28. Soil moisture measuring devices**

i. Gravimetric technique. The oven or microwave oven drying of a known weight of soil to determine the weight of moisture contained in the sample (ASTM D2216-19, 2019; ASTM D4643-17, 2017; ASTM D4959-16, 2016; Society of Automotive Engineers, 1967b).
ii. Gas pressure technique. The measure of moisture content in a small soil sample derived from the pressure of the gas generated when the water in the soil combines with calcium carbide (Blystone et al., 1962; ASTM D4944-18, 2018).
iii. Electrical probe*. An instrument used to determine the moisture content of non-saturated soils. Moisture content may be determined from the electrical resistance of the soil. The instrument must be calibrated for each soil studied (U.S. Army Engineer Waterways Experiment Station, 1962). An in-use method in this type is the complex impedance method. In this the electrical properties of the soil are measured by application of the radio frequency voltage to the electrical probes installed in the soil. These electrical properties are then further used for calibration and determination of water content. (ASTM D7698-19, 2019)
iv. Nuclear technique. The measurement of neutrons from a known source which are scattered by the soil to determine the number of hydrogen atoms in a given sample. Since there are few hydrogen atoms in soil, this measurement represents the moisture content of the soil (ASTM D6938-17a, 2017).
v. Time Domain Reflectometry (TDR) technique. The indirect measurement of soil water content based on the travel time of a high-frequency electromagnetic pulse through the soil. The travel time is measured by using a multiple rod probe, a coaxial head, and a TDR apparatus, and converted to the dielectric constant of the soil. The soil water content is obtained by using a correlation between the dielectric constant, water content, and soil density (determined by using the measured mass of the sampled soil and the measured volume of the sampler). (ASTM D6780/D6780M-19, 2019)
vi. Electromagnetic impedance spectroscopy device**. The device that measures the electromagnetic properties of the soil as a function of frequency; this function is compared with an empirical model and other calibration checks to determine the volumetric water content (ASTM D7830/D7830M-14, 2014),

3.29. Taper penetrometer

An instrument used to measure the strength of soil, weighing about 2.94 kg (6.5 lb.). It consists of a hollow shaft in the shape of a four-sided, 3° pyramid. The shaft is graduated in 25.4 mm (1 in.) increments to 762 mm (30 in.), with a spring-type loading device mounted on top. The spring which connects the two arms can be adjusted so that when the arms are depressed to reach a nearly horizontal position, a constant force is applied. The depth to which the taper penetrates the soil is a measure of its strength. The remolding effect is determined by measuring the increase in penetration that results from twisting the instrument while the maximum load is maintained (U.S. Army Engineer Waterways Experiment Station, 1955; U.S. Army Engineer Waterways Experiment Station, 1960).

*3.30. Torque tube**

An instrument used to measure the in situ snow cohesion c_s and angle of internal friction φ_s by rotating it under different normal loads in snow. The equipment consists of a thin-walled tube with

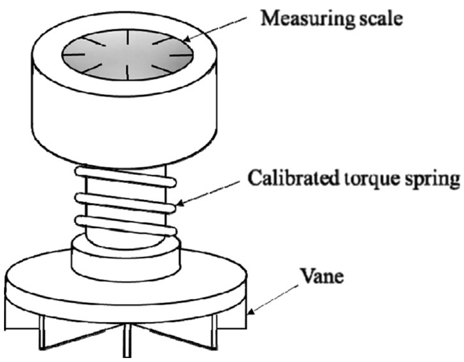


Fig. 44. Schematic of a torvane.

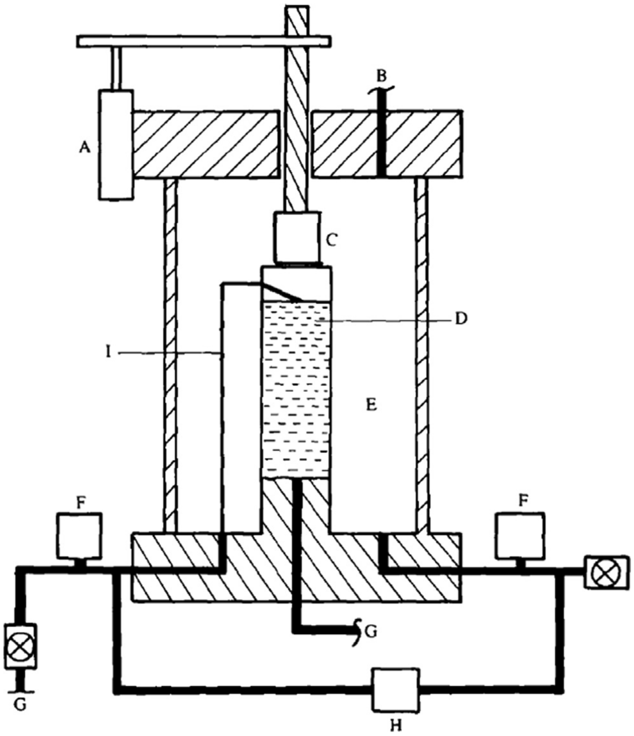


Fig. 45. Schematic of a typical triaxial test apparatus. (A) Film pot (B) Chamber pressure (C) Load cell (D) Test specimen (E) Chamber fluid (F) Pressure transducer (G) Back pressure (H) Differential pressure transducer (I) Top drainage line (Okello, 1991). Chamber fluid (E) exerts pressure to the test specimen (D); an axial load is applied to the test specimen and measured by a load cell (C). Reprinted from (Okello, 1991) with permission of Elsevier.

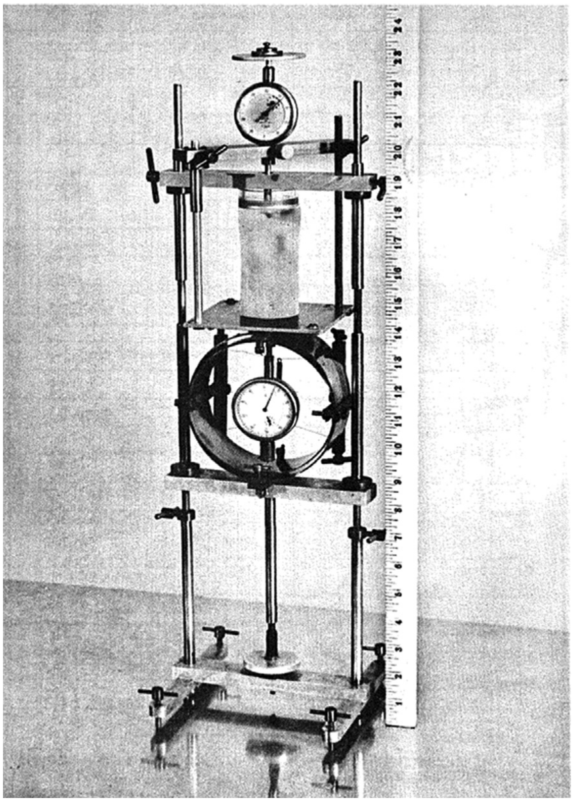


Fig. 46. Unconfined compression test apparatus (U.S. Army Engineer Waterways Experiment Station, 1955). The soil sample was placed between two circular plates, one of which could move up and down relative to the other. Reprinted from (U.S. Army Engineer Waterways Experiment Station, 1955) with permission of US Army Engineer Research & Development Center.

a set of thin vanes placed at right-angles to each other inside one end of the tube. The other end is equipped with a torque measuring apparatus and a set of weights. The torque tube is loaded at various normal loads and placed on the snow; the torque readings are recorded at the maximum torque required to shear the snow and at the torque required to maintain rotation of the tube after the snow shear has happened (U.S. Army Engineer Waterways Experiment Station, 1960; Diamond and Hansen, 1956).

*3.31. Torvane**

A type of shear vane used to rapidly measure the shear strength of cohesive soils (soil cohesion c_v) in the laboratory or field (Fig. 44). As a hand-held, portable tool, the torvane mainly consists of (1) one vane or multiple interchangeable vanes (2) calibrated torque spring and (3) a measuring scale (ASTM D8121/D8121M-18, 2018). The calibrated torque spring and measuring scale convert torque directly into the shear stress and record the maximum shear stress during the rotation of the vane until the soil failure happens.

For the standard test method for shear tests using a torvane, see (ASTM D8121/D8121M-18, 2018).

*3.32. Triaxial test apparatus**

An instrument used to apply normal stresses in three perpendicular directions on a cylindrical specimen of soil and measure the shear strength of soil under undrained or controlled drainage conditions (Fig. 45). Typical triaxial test apparatus essentially consists of a compression chamber containing a relatively incompressible fluid (the fluid compression chamber). The bottom of the chamber is fitted with a porous plug while the top is fitted with a vertical loading device. A cylindrical soil sample being tested is encased in a rubber membrane and placed in the chamber. The fluid surrounding the soil sample is subjected to a predetermined pressure while the sample is loaded axially until failure (ASTM D2850-15, 2015; Society of Automotive Engineers, 1967b).

Also, a triaxial test apparatus has been developed to feature the capability of applying independently controlled stress in three directions (Reddy et al., 1992). Unlike typical triaxial test apparatus, this triaxial test apparatus has no fluid compression chamber.

For off-road vehicle mobility study, the triaxial test apparatus is usually used to determine the soil cohesion, c_t, and angle of internal friction, φ_t.

For the standard test methods for triaxial shear tests, see (AASHTO T 296, 2010; ASTM D4767-11, 2011; ASTM D2850-15, 2015; ASTM D5311/D5311M-13, 2013; ASTM D7181-11, 2011; ASTM D5202/D5202M-16, 2016; ISO 17892-8:2018, 2018; ISO 17892–9:2018, 2018).

*3.33. Unconfined compression test apparatus**

An instrument used to measure the unconfined compressive strength of a cohesive soil (Fig. 46). A soil specimen of known dimensions is placed between the compression members of the apparatus, e.g., a fixed plate and a moving plate, and loaded at a constant rate of strain until failure (ASTM D2166/D2166M-16, 2016).

For the standard test methods for unconfined compression test, see (ASTM D2166/D2166M-16, 2016; ISO 17892-7:2017, 2017).

3.34. Vane Cone**

An instrument combining the penetration resistance measurement of the cone penetrometer and the shear strength measurement of the shear vane, used in the in situ test. The vane-cone is pressed into the soil and then, at a specified depth, is rotated while the depth is held constant (Shoop, 1993).

4. Suggestions for standard test methods

Several societies provide standard test methods for soil tests and soil parameters measurement, as shown under the relevant terms in this document. Examples include ASTM international, American Society of Agricultural and Biological Engineers (ASABE), International Organization for Standardization (ISO), etc. It is suggested that the standard test methods provided by these societies are followed for the soil tests and soil parameters measurement in the study of off-road mobility and terramechanics. However, some special soil tests, crucial in the study of off-road mobility and terramechanics, have not been standardized by the aforementioned societies. Among them are the sinkage test using plates, shear tests using shear plates or traction elements, and remolding tests; the SAE recommended practice "Off-Road Vehicle Mobility Evaluation – SAE J939" (Society of Automotive Engineers, 1967b) prescribed test methods for these tests. Nevertheless, this SAE recommended practice has not been updated ever since its debut release in 1967; some of the content could be outdated. It is suggested that the ISTVS draft standard test methods for the sinkage test using plates, shear tests using shear plates or traction elements, and remolding tests.

The description under some terms in this document shows that multiple standard measurement methods exist for one test or the measurement of one soil parameter. Measurement of some soil parameters, e.g., bulk density and water content, can be made via a direct measurement method that serves as the benchmark for other indirect measurement methods; the standard measurement methods for these soil parameters can be categorized as direct methods and indirect methods. A direct measurement method is suggested to be executed because, theoretically, it directly measures a soil parameter instead of estimating that soil parameter as an indirect measurement method does. However, applying a direct measurement method may disturb the soil condition of interest if sampling is required in the direct measurement method. Given that in the field test, it is hard to restore the soil condition of interest once it is disturbed, an indirect measurement could be preferred in the field test. Also, some measurement methods take a long time to be completely implemented. This might make the measurement result deviate from the true value in the soil condition of interest if the soil condition has varied considerably, e.g., in terms of moisture content, since the moment the soil is sampled in these measurement methods. Also, it is possible that the equipment specified in the standard measurement methods is different from the available equipment. In this case, the standard measurement method in which the specified equipment is most similar to the available equipment is suggested to be applied. Therefore, it can be seen that when it comes to selecting a standard measurement method among many options, a balance must be struck between the measurement accuracy, the deviation from the soil condition of interest, and the equipment availability.

To determine the shear strength of soil, soil cohesion, soil friction angle, and/or shear stress-shear deformation relationship, multiple standard measurement methods exist as described in Section 2, Section 3, and the study (Okello, 1991). The rule of thumb (He et al., 2019) for choosing a standard measurement method is to ensure that the shear behavior in the standard measurement method closely resembles the shear behavior of interest in terms of the shearing type, i.e., the internal shearing of soil (e.g., for the traction or transport elements with lugs) or the shear tool-soil shearing; of the shearing direction, i.e., torsional shearing or translational shearing; and of the shearing rate, i.e., the shearing rate may need to be equal to the slip velocity of the running gear to be modelled (Wong et al., 1984). In the study of off-road mobility and terramechanics, the type of soil condition is the unconsolidated and undrained (Society of Automotive Engineers, 1967b) with which the specified soil condition in the selected standard measurement method should match.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been partially supported by the ISTVS Research Grant Award, U.S. Army Engineer Research and Development Center (ERDC), NSF I/UCRC Center for Tire Research (CenTiRe), Vehicle Dynamics Group at University of Pretoria, and Terramechanics, Multibody, and Vehicle Systems (TMVS) Laboratory at Virginia Tech. We also want to thank all ISTVS members who contributed with their comments or reviews of this document.

References

AASHTO M 145-91 (2012), 2012. Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes, AASHTO Standards. AASHTO, Washington, DC.

AASHTO T 236, 2018. Standard Method of Test for Direct Shear Test of Soils under Consolidated Drained Conditions. AASHTO, Washington, DC.

AASHTO T 296, 2010. Standard Method of Test for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression. AASHTO, Washington, DC.

Adam, K.M., Erbach, D.C., 1995. Relationship of tire sinkage depth to depth of soil compaction. Trans. ASAE 38, 1011–1016. https://doi.org/10.13031/2013.27917.

Andrews, L.A., Broadfoot, W.M., 1958. The san dimas soil core sampler. Soil Sci. 85, 297–301. https://doi.org/10.1097/00010694-195806000-00002.

ANSI/ASAE S296.5 DEC2003 (R2018), 2018. General Terminology for Traction of Agricultural Traction and Transport Devices and Vehicles. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan.

Armbruster, K., Kutzbach, H.D., 1991. Combined lateral and longitudinal forces on driven angled tractor tyres. J. Terramech. 28, 331–338. https://doi.org/10.1016/0022-4898(91)90014-W.

ASAE EP542 FEB1999 (R2018), 2018. Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

ASAE S313.3 FEB1999 (R2018), 2018. Soil Cone Penetrometer. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Asaf, Z., Rubinstein, D., Shmulevich, I., 2006. Evaluation of link-track performances using DEM. J. Terramech. 43, 141–161. https://doi.org/10.1016/j.jterra.2004.10.004.

ASTM D1452/D1452M-16, 2016. Standard Practice for Soil Exploration and Sampling by Auger Borings. ASTM International, West Conshohocken, PA. Doi: 10.1520/D1452_D1452M-16.

ASTM D1556/D1556M-15e1, 2015. Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method. ASTM International, West Conshohocken, PA. Doi: 10.1520/D1556_D1556M-15E01.

ASTM D1558-10, 2010. Standard Test Method for Moisture Content Penetration Resistance Relationships of Fine-Grained Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D1558-10.

ASTM D1587/D1587M-15, 2015. Standard Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes. ASTM International, West Conshohocken, PA. Doi: 10.1520/D1587_D1587M-15.

ASTM D1883-16, 2016. Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D1883-16.

ASTM D2166/D2166M-16, 2016. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2166_D2166M-16.

ASTM D2167-15, 2015. Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2167-15.

ASTM D2216-19, 2019. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2216-19.

ASTM D2487-17, 2017. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA. Doi: 10.1520/D2487-17.

ASTM D2573/D2573M-18, 2018. Standard Test Method for Field Vane Shear Test in Saturated Fine-Grained Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2573_D2573M-18.

ASTM D2850-15, 2015. Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2850-15.

ASTM D2937-17e2, 2017. Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2937-17E02.

ASTM D2944-14, 2014. Standard Practice of Sampling Processed Peat Materials. ASTM International, West Conshohocken, PA. Doi: 10.1520/D2944-14.

ASTM D3080/D3080M-11, 2011. Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. ASTM International, West Conshohocken, PA. Doi: 10.1520/D3080_D3080M-11.

ASTM D3441-16, 2016. Standard Test Method for Mechanical Cone Penetration Testing of Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D3441-16.

ASTM D4254-16, 2016. ASTM D4254-00: Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4254-16.

ASTM D4318−17, 2017. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4318-17E01.

ASTM D4643-17, 2017. Standard Test Method for Determination of Water Content of Soil and Rock by Microwave Oven Heating. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4643-17.

ASTM D4648/D4648M-16, 2016. Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4648_D4648M-16.

ASTM D4700-15, 2015. Standard Guide for Soil Sampling from the Vadose Zone. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4700-15.

ASTM D4767-11, 2011. Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4767-11.

ASTM D4914/D4914M-16, 2016. Standard Test Methods for Density of Soil and Rock in Place by the Sand Replacement Method in a Test Pit. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4914_D4914M-16.

ASTM D4943-18, 2018. Standard Test Method for Shrinkage Factors of Soils by the Wax Method. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4943-18.

ASTM D4944-18, 2018. Standard test method for Field determination of water (moisture) content of soil by the calcium carbide gas pressure tester. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4944-18.

ASTM D4959-16, 2016. Standard Test Method for Determination of Water (Moisture) Content of Soil By Direct Heating. ASTM International, West Conshohocken, PA. Doi: 10.1520/D4959-16.

ASTM D5030/D5030M−13a, 2013. Standard Test Methods for Density of Soil and Rock in Place by the Water Replacement Method in a Test Pit. ASTM International, West Conshohocken, PA. Doi: 10.1520/D5030_D5030M-13A.

ASTM D5202/D5202M-16, 2016. Standard Test Method for Determining Triaxial Compression Creep Strength of Chemically Grouted Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D5202.

ASTM D5311/D5311M-13, 2013. Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil. ASTM International, West Conshohocken, PA. Doi: 10.1520/D5311_D5311M-13.

ASTM D5550-14, 2014. Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer. ASTM International, West Conshohocken, PA. Doi: 10.1520/D5550-14.

ASTM D6528-17, 2017. Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Fine Grain Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D6528-17.

ASTM D653-14, 2014. Standard Terminology Relating to Soil, Rock, and Contained Fluids. ASTM International, West Conshohocken, PA. Doi: 10.1520/D0653-14.2.

ASTM D6780/D6780M-19, 2019. Standard Test Methods for Water Content and Density of Soil In situ by Time Domain Reflectometry (TDR). ASTM International, West Conshohocken, PA. Doi: 10.1520/D6780_D6780M-19.

ASTM D6913/D6913M-17, 2017. Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM International, West Conshohocken, PA. Doi: 10.1520/D6913_D6913M-17.

ASTM D6938-17a, 2017. Standard Test Methods for In-Place Density and Water Content of Soil and Soil Aggregate by Nuclear Methods (Shallow Depth). ASTM International, West Conshohocken, PA. Doi: 10.1520/D6938-17A.

ASTM D6951/D6951M–18, 2018. Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications. ASTM International, West Conshohocken, PA. Doi: 10.1520/D6951_D6951M-18.

ASTM D698-12e2, 2012. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)). ASTM International, West Conshohocken, PA. Doi: 10.1520/D0698-12E02.

ASTM D7181-11, 2011. Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7181-11.

ASTM D7263-09(2018)e2, 2018. Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7263-09R18E02.

ASTM D7380−15, 2015. Standard Test Method for Soil Compaction Determination at Shallow Depths Using 5-lb (2.3 kg) Dynamic Cone Penetrometer. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7380-15.

ASTM D7698-19, 2019. Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7698-19.

ASTM D7830/D7830M-14, 2014. Standard Test Method for In-Place Density (Unit Weight) and Water Content of Soil Using an Electromagnetic Soil Density Gauge. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7830_D7830M-14.

ASTM D7928-17, 2017. Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. ASTM International, West Conshohocken, PA. Doi: 10.1520/D7928-17.

ASTM D8121/D8121M-18, 2018. Standard Test Method for Approximating the Shear Strength of Cohesive Soils by the Handheld Vane Shear Device. ASTM International, West Conshohocken, PA. Doi: 10.1520/D8121_D8121M-18.

ASTM D854-14, 2014. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International, West Conshohocken, PA. Doi: 10.1520/D0854-14.

Bader, H., Hansen, B.L., Joseph, J.A., Sandgren, M.A., 1951. Preliminary Investigations of Some Physical Properties of Snow. Engineering Experiment Station, Institute of Technology, University of Minnesota, and U.S. Army Snow, Ice, and Permafrost Research Establishment.

Bekker, M.G., 1969. Introduction to Terrain-Vehicle Systems. Part I: The Terrain. Part II: The Vehicle. University of Michigan, Ann Arbor, Michigan.

Blackmon, C.A., Knight, S.J., Rone, C.L., 1963. Studies of Aerial Cone Penetrometer; Field Tests in Fine-Grained Soils, 1960. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Blystone, J.R., Pelzner, A., Steffens, G.P., 1962. Moisture content determination by the calcium carbide gas pressure method, in: Highway Research Board Bulletin, 40th Annual Meeting. Highway Research Board, pp. 77–84.

Braunack, M.V., 1986. Changes in physical properties of two dry soils during tracked vehicle passage. J. Terramech. 23, 141–151. https://doi.org/10.1016/0022-4898(86)90003-0.

Brixius, W.W., 1987. Traction prediction equations for bias ply tires. ASAE Paper No. 87-1622. American Society of Agricultural Engineers, St. Joseph, MI.

Burns, C.D., Carr, G.L., 1965. Operational Test of Modified T11 Aluminum Landing Mat, England AFB, Louisiana. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Cohron, G.T., 1963. Soil sheargraph. Agr. Eng. 44, 554–556.

Contreras, U., Li, G., Foster, C.D., Shabana, A.A., Jayakumar, P., Letherwood, M.D., 2013. Soil Models and Vehicle System Dynamics. Appl. Mech. Rev. 65, 041001. https://doi.org/10.1115/1.4024759.

Cossalter, V., 2006. Motorcycle Dynamics. LULU Press Inc..

Day, A., 2014. Brake System Layout Design, in: Braking of Road Vehicles. Butterworth-Heinemann, pp. 149–213. Doi: 10.1016/C2011-0-07386-6.

Diamond, M.., Hansen, B.L., 1956. Use of a Shear Vane in Snow. Engineer Research and Development Center (U.S.); U.S. Army Snow, Ice, and Permafrost Research Establishment.

Fenwick, W.B., 1965. Description and application of airfield cone penetrometer. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Freitag, D.R., 1965. A Dimensional Analysis of the Performance of Pneumatic Tires on Soft Soils. U.S. Army Engineer Waterways Experiment Station, Engineer Research and Development Center (U.S.), Vicksburg, Mississippi.

Freitag, D.R., Green, A.J., Melzer, K.J., 1970. Performance evaluation of wheels for lunar vehicles, Technical report M-70-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Gardner, W.H., 1986. Water content, in: Klute, A. (Ed.), Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods, SSSA Book Ser. 5.1. Soil Science Society of America, American Society of Agronomy, Madison, WI, pp. 493–544. Doi: 10.2136/sssabookser5.1.2ed.c21.

Genta, G., 2010. Conventional and slip steering for multi-wheel planetary rovers. Acc. Sc. Torino Mem. Sc. Fis. Mecc. DEI SOLIDI 34, 38.

Gonzalez, R., Apostolopolous D., I.K., 2019. Improving rover mobility through traction control: simulating rovers on the Moon. Auton. Robots 43, 1977–1988. Doi: 10.1007/s10514-019-09846-3.

Gonzalez, R., Iagnemma, K., 2018. Slippage estimation and compensation for planetary exploration rovers. State of the art and future challenges. J. F. Robot. 35, 564–577. https://doi.org/10.1002/rob.21761.

Grau, R.W., 1981. C-5A Operational Utility Evaluation Soil Tests and Analysis. Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53, 71–85. https://doi.org/10.1016/S0167-1987(99)00095-1.

He, R., Khan, A.K., Guthrie, A.G., Sandu, C., Els, P.S., 2017. A technical survey on terminology , testing methodologies , and equipment used in modeling and parameterization of soft soil for vehicular applications, in: Proceedings of the

19th International and 14th European-African Regional Conference of the ISTVS, Budapest, September 25-27, 2017. ISTVS, Budapest, Hungary, pp. 1–39.

He, R., Sandu, C., Khan, A.K., Guthrie, A.G., Schalk Els, P., Hamersma, H.A., 2019. Review of terramechanics models and their applicability to real-time applications. J. Terramech. 81, 3–22. https://doi.org/10.1016/j.jterra.2018.04.003.

Hegazy, S., Sandu, C., 2013. Experimental investigation of vehicle mobility using a novel wheel mobility number. J. Terramech. 50, 303–310. https://doi.org/10.1016/j.jterra.2013.09.005.

Huang, W., Wong, J.Y., Preston-Thomas, J., Jayakumar, P., 2020. Predicting terrain parameters for physics-based vehicle mobility models from cone index data. J. Terramech. 88, 29–40. https://doi.org/10.1016/j.jterra.2019.12.004.

International Society of Soil Science, 1929. Minutes of the first commission meetings, International Congress of Soil Science, in: The Congress of the International Society of Soil Science. International Society of Soil Science, Washington, DC, pp. 215–220.

Ishigami, G., 2008. Terramechanics-based analysis and control for lunar/ planetary exploration robots. Tohoku University.

ISO 11272:2017, 2017. Soil quality – Determination of dry bulk density, 2nd ed. ISO/TC 190/SC 3 Chemical and physical characterization.

ISO 11277:2009, 2009. Soil quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation. ISO/TC 190/SC 3 Chemical and physical characterization.

ISO 11465:1993, 1993. Soil quality – Determination of dry matter and water content on a mass basis – Gravimetric method. ISO/TC 190/SC 3 Chemical and physical characterization.

ISO 17892-1:2014, 2014. Geotechnical investigation and testing – Laboratory testing of soil – Part 1: Determination of water content. ISO/TC 182 Geotechnics.

ISO 17892-10:2018, 2018. Geotechnical investigation and testing – Laboratory testing of soil – Part 10: Direct shear tests. ISO/TC 182 Geotechnics.

ISO 17892-12:2018, 2018. Geotechnical investigation and testing – Laboratory testing of soil – Part 12: Determination of liquid and plastic limits. ISO/TC 182 Geotechnics.

ISO 17892-2:2014, 2014. Geotechnical investigation and testing – Laboratory testing of soil – Part 2: Determination of bulk density. ISO/TC 182 Geotechnics.

ISO 17892-4:2016, 2016. Geotechnical investigation and testing – Laboratory testing of soil – Part 4: Determination of particle size distribution. ISO/TC 182 Geotechnics.

ISO 17892-7:2017, 2017. Geotechnical investigation and testing – Laboratory testing of soil – Part 7: Unconfined compression test. ISO/TC 182 Geotechnics.

ISO 17892-8:2018, 2018. Geotechnical investigation and testing – Laboratory testing of soil – Part 8: Unconsolidated undrained triaxial test, 1st ed. ISO/TC 182 Geotechnics.

ISO 17892-9:2018, 2018. Geotechnical investigation and testing – Laboratory testing of soil – Part 9: Consolidated triaxial compression tests on water saturated soils. ISO/TC 182 Geotechnics.

Jahn, R., Blume, H.P., Asio, V.B., Spaargaren, O., Schad, P., 2006. Guidelines for soil description. Food and Agriculture Organization of the United Nations, Rome.

Jazar, R.N., 2014. Vehicle Dynamics: Theory and Application, 2nd ed. Springer-Verlag New York. Doi: 10.1007/978-1-4614-8544-5

Johnson, A.W., Sallberg, J.R., 1960. Factors That Influence Field Compaction of Soils, Highway Research Board Bulletin. Highway Research Board, Washington, D.C.

K. Kogure, H. Yamaguchi, Y.O., 1988. Comparison of strength and soil thrust characteristics among different soil shear tests. J. Terramechanics 25, 201–221. Doi: 10.1016/0022-4898(88)90003-1

Kees, G., 2005. Hand-Held Electronic Cone Penetrometers for Measuring Soil Strength, 2E22E60—Soil Strength Tester. USDA Forest Service, Technology and Development Program, Missoula, MT.

Kirby, J.M., McLachlan, C.B., Blunden, B.G., 1994. Calibration of a sheargraph. Soil Tillage Res. 31, 1–9. https://doi.org/10.1016/0167-1987(94)90090-6.

Kiss, P., 2003. Rolling radii of a pneumatic tyre on deformable soil. Biosyst. Eng. 85, 153–161. https://doi.org/10.1016/S1537-5110(03)00043-6.

Knight, S.J., Freitag, D.R., 1962. Measurement of Soil Trafficability Characteristics. Trans. ASAE 121–124. https://doi.org/10.13031/2013.40954.

Kutzbach, H.D., Bürger, A., Böttinger, S., 2019. Rolling radii and moment arm of the wheel load for pneumatic tyres. J. Terramech. 82, 13–21. https://doi.org/10.1016/j.jterra.2018.11.002.

Kutzbach, H.D., Witzel, P., Schreiber, M., 2009. Single Wheel Field Tester for Farm Tractor Tyres A Review, in: 11th European Regional Conference of the ISTVS. International Society for Terrain-Vehicle-Systems, Bremen, Germany.

Landva, A., Pheeney, P., Mersereau, D., 1983. Undisturbed sampling of peat. Test. Peats Org. Soils 141–156. https://doi.org/10.1520/STP37340S.

Lemaitre, J., 2001. Handbook of Materials Behavior Models, Three-Volume Set: Nonlinear Models and Properties. Elsevier Inc.

Liu, C.H., Wong, J.Y., Mang, H.A., 2000. Large strain finite element analysis of sand: model, algorithm and application to numerical simulation of tire-sand interaction. Comput. Struct. 74, 253–265. https://doi.org/10.1016/S0045-7949(99)00049-8.

Lyasko, M., 2010a. LSA model for sinkage predictions. J. Terramech. 47, 1–19. https://doi.org/10.1016/j.jterra.2009.06.004.

Lyasko, M.I., 2010b. How to calculate the effect of soil conditions on tractive performance. J. Terramech. 47, 423–445. https://doi.org/10.1016/j.jterra.2010.04.003.

Matsuoka, H., Liu, S., Sun, D., Nishikata, U., 2001. Development of a New In-Situ Direct Shear Test. Geotech. Test. J. 24, 92–102. https://doi.org/10.1520/GTJ11285J.

McRae, J.L., Powell, C.J., Wismer, R.D., 1965. Performance of Soils Under Tire Loads. Report 1, Test Facilities and Techniques, Technical Report NO. 3-666. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Meyer, M.P., Ehrlich, I.R., Sloss, D., Murphy, N.R., Wismer, R.D., Czako, T., 1977. International society for terrain-vehicle systems standards. J. Terramech. 14, 153–182. https://doi.org/10.1016/0022-4898(77)90013-1.

Meyer, M.P., Knight, S.J., 1961. Trafficability of Soils: Soil Classification. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Mills, H.L., Clagg, S.E., 1964. The physiognomy of vegetation: a quantitative approach to vegetation geometry based on the structural cell concept as a minimal sample size. Marshall University, Huntington, West Virginia.

Mobility and Environmental Systems Laboratory (U.S.), 1958. Studies of Aerial Cone Penetrometer. Report 2, Field Tests. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Mobility and Environmental Systems Laboratory (U.S.), 1957. Studies of Aerial Cone Penetrometer. Report 1, Laboratory Study of Mechanical Principles. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Murano, H., Takata, Y., Isoi, T., 2015. Soil Science and Plant Nutrition Origin of the soil texture classification system used in Japan Origin of the soil texture classification system used in Japan. Soil Sci. Plant Nutr. 61, 688–697. https://doi.org/10.1080/00380768.2014.998594.

Muro, T., O'Brien, J., 2004. Terramechanics: land locomotion mechanics. CRC Press.

Nakashima, H., Oida, A., 2004. Algorithm and implementation of soil–tire contact analysis code based on dynamic FE–DE method. J. Terramech. 41, 127–137. https://doi.org/10.1016/j.jterra.2004.02.002.

Naranjo, S.D., Sandu, C., Taheri, S., Taheri, S., 2014. Experimental Testing of an Off-Road Instrumented Tire on Soft Soil. J. Terramech. 56, 119–137. https://doi.org/10.1016/j.jterra.2014.09.003.

Niedringhaus, L., 1965. Study of the Rammsonde for Use in Hard Snow. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Office of the Chairman of the Joint Chiefs of Staff, 2019. Department of Defense Dictionary of Military and Associated Terms. The Joint Staff, Washington, DC.

Okello, A., 1991. A review of soil strength measurement techniques for prediction of terrain vehicle performance. J. Agric. Eng. Res. 50, 129–155. https://doi.org/10.1016/S0021-8634(05)80010-1.

Pacejka, H.B., 2005. Tire and Vehicle Dynamics. Butterworth-Heinemann.

Perumpral, J.V., 1987. Cone penetrometer applications — a review. Trans. ASAE 30, 939–944.

Pitkänen, A., Turunen, J., Simola, H., 2011. Comparison of different types of peat corers in volumetric sampling. Suo 62, 51–57.

Quick, J., 1973. Dictionary of Weapons and Military Terms. McGraw-Hill.

Rajamani, R., 2012. Vehicle Dynamics and Control, second ed., Mechanical Engineering Series. Springer US. Doi: 10.1007/978-1-4614-1433-9.

Reddy, K.R., Saxena, S.K., Budiman, J.S., 1992. Development of a true triaxial testing apparatus. Geotech. Test. J. 15, 89–105. https://doi.org/10.1520/GTJ10231J.

Reece, A.R., 1965. Principles of soil-vehicle mechanics. Proc. Inst. Mech. Eng. Automob. Div. 180, 45–46. 10.1243%2FPIME_AUTO_1965_180_009_02.

Rula, A.A., Nuttall, C.J., 1971. An analysis of ground mobility models (ANAMOB). U.S. Army Engineer Waterways Experimental Station, Vicksburg, Mississippi.

Schertmann, J., 1977. Guidelines for cone penetration test: performance and design, no. FHWA-TS-78-209. United States. Federal Highway Administration.

Seaby, D., 2001. Designs for one-man, two-stage, samplers for obtaining undisturbed cores of peat over 1 m long. Forestry 74, 79–83.

Shoop, S., Young, B., Algert, R., Davis, J., 1994. Effect of test method on winter traction measurements. J. Terramech. 31, 153–161. https://doi.org/10.1016/0022-4898(94)90012-4.

Shoop, S.A., 1993. Terrain Characterization for Trafficability. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Society of Automotive Engineers, 2008. Vehicle dynamics terminology, SAE J670. SAE International, New York, NY.

Society of Automotive Engineers, 1967a. Soil-Vehicle Terminology, SAE J991, 1968 SAE Handbook. SAE International, New York, NY.

Society of Automotive Engineers, 1967b. Off-Road Vehicle Mobility Evaluation, SAE J939, Handbook supplement. SAE International, New York, NY.

Soil Science Division Staff, 2017. Soil survey manual, Agricultural Handbook No. 18. United States Department of Agriculture, Washington, DC. Doi: 10.2307/1233734.

Soil Survey Staff, 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys, 2nd ed. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436. Doi: 10.1097/00010694-197704000-00011.

Stevens, M.T., Towne, B.W., Mason, G.L., Priddy, J.D., Osorio, J.E., Barela, C.A., 2013. Procedures for One-Pass Vehicle Cone Index (VCI1) Determination for Acquisition Support. Geotechnical and Structures Laboratory, US Army Engineer Research and Development Center, Vicksburg, Mississippi.

Taheri, S., Sandu, C., Taheri, S., Pinto, E., Gorsich, D., 2015. A technical survey on Terramechanics models for tire-terrain interaction used in modeling and simulation of wheeled vehicles. J. Terramech. 57, 1–22. https://doi.org/10.1016/j.jterra.2014.08.003.

Tai, M., Tomizuka, M., 2000. Robust longitudinal velocity tracking of vehicles using traction and brake control, in: 6th International Workshop on Advanced Motion Control. Proceedings (Cat. No. 00TH8494). IEEE, pp. 305–310. Doi: 10.1109/amc.2000.862881.

The Staffs of the Surface Mobility Division (TACOM) and the Mobility and Environmental Laboratory (WES), 1973. The AMC '71 Mobility Model, Technical Report NO. 11789 (LL 143). U.S. Army Tank Automotive Command, Warren, Michigan.

Tripartite Working Group on Ground Mobility, 1961. Proposed dictionary of ground mobility terms, in: Rept. Third Conference. Office of the Chief, Research and Development, U.S. Army, Washington, DC.

Turnage, G.W., 1972. Performance of Soils Under Tire Loads. Report 8, Application of Test Results to Tire Selection for Off-Road Vehicles. U.S. Army Engineer Waterways Experiment Station, Engineer Research and Development Center (U.S.), Vicksburg, Mississippi.

U.S. Army Engineer Waterways Experiment Station, 1962. Plan of tests tropical soil studies in Panama and Puerto Rico. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

U.S. Army Engineer Waterways Experiment Station, 1960. Trafficability of Snow, Greenland Studies, 1955 and 1957. U.S. Army Engineer Waterways Experiment Station, Engineer Research and Development Center (U.S.), Vicksburg, Mississippi.

U.S. Army Engineer Waterways Experiment Station, 1955. Trafficability of Snow, Greenland Studies 1954. U.S. Army Engineer Waterways Experiment Station, Engineer Research and Development Center (U.S.), Vicksburg, Mississippi.

U.S. Army Engineer Waterways Experiment Station, 1954. Forecasting Trafficability of Soils: Report No. 3, the Development of Methods for Predicting Soil Moisture Content, Volume 2, Prediction Sites at Vicksburg, Mississippi. U.S. Army Engineer Waterways Experiment Station, Engineer Research and Development Center (U.S.), Vicksburg, Mississippi.

U.S. Army Material Command, 1965. The Automotive assembly, in: Engineering Design Handbook. National Technical Information Service, Washington, DC.

U.S. Army Transportation Combat Developments Agency, 1962. Logistical Vehicle Off-Road Mobility, Final Rept. Project TCCD 62-5. Fort Eustis, Virginia.

U.S. Department of Defense, 1968. Glossary of Environmental Terms(Terrestrial), Military Standard MIL-STD-1165. Washington, DC.

Ueda, H.T., Sellmann, P. V., Abele, G., 1975. USA CRREL Snow and Ice Testing Equipment. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

United States Department of the Army, 2001. Materials testing. Field manual FM 5-472, Field manual, FM 5-472.; Naval Facilities Engineering Command, NAVFAC MO 330; Air Force joint manual, AFJMAN 32-1221(I); Departments of the Army, Washington, DC.

United States Department of the Army and the Air Force, 1968. Planning and design of roads, airbases, and heliports in the theater of operations, Department of the Army technical manual, TM 5-330.; Air Force manual, AFM 86-3, vol. II. Departments of the Army and Air Force, Washington, DC.

Upadhyaya, S.K., Wulfsohn, D., Mehlschau, J., 1993. An instrumented device to obtain traction related parameters. J. Terramech. 30, 1–20. https://doi.org/10.1016/0022-4898(93)90027-U.

US Army Corps of Engineers, 1970. Engineering and Design Laboratory Soils Testing, USACE Engineer Manual EM 1110-2-1906. US Department of the Army, Washington, DC.

US army test and evaluation command, 1981. Weight distrubution and ground pressure (Wheeled and Tracked Vehicles). Us army test and evaluation command, Maryland, USA.

USAE Waterways Experiment Station, 1963. Environmental factors affecting ground mobility in Thailand, Preliminary Survey. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

van Asselen, S., Roosendaal, C., 2009. A new method for determining the bulk density of uncompacted peat from field settings. J. Sediment. Res. 79, 918–922. https://doi.org/10.2110/jsr.2009.091.

Vaz, C.M.P., Hopmans, J.W., 2001. Simultaneous Measurement of Soil Penetration Resistance and Water Content with a Combined Penetrometer–TDR Moisture Probe. Soil Sci. Soc. Am. J. 65, 4–12. https://doi.org/10.2136/sssaj2001.6514.

Webster, S.L., Grau, R.H., Williams, T.P., 1992. Description and Application of Dual Mass Dynamic Cone Penetrometer, INSTRUCTION REPORT GL-92-3. Geotechnical Laboratory (U.S.), Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.

Wismer, R.D., 1965. Identification of design parameters for off-road mobility problems. In: Proceedings of ISTVS Meeting at Houghton, Michigan. ISTVS, Houghton, MI.

Wismer, R.D., Luth, H.J., 1973. Off-road traction prediction for wheeled vehicles. J. Terramech. 10, 49–61. https://doi.org/10.1016/0022-4898(73)90014-1.

Wong, J.-Y., Reece, A.R., 1967. Prediction of rigid wheel performance based on the analysis of soil-wheel stresses part I. Performance of driven rigid wheels. J. Terramech. 4, 81–98. https://doi.org/10.3724/SP.J.1260.2012.20007.

Wong, J.Y., 2009. Terramechanics and Off-road Vehicle Engineering: Terrain Behaviour, Off-road Vehicle Performance and Design. Butterworth-Heinemann, Oxford.

Wong, J.Y., 2008. Theory of Ground Vehicles. John Wiley & Sons.

Wong, J.Y., Garber, M., Preston-Thomas, J., 1984. Theoretical prediction and experimental substantiation of the ground pressure distribution and tractive performance of tracked vehicles. Proc. Inst. Mech. Eng. Part D Transp. Eng. 198, 265–285.

Wulfsohn, D., Adams, B.A., 2002. Elastoplastic soil mechanics, in: Advances in Soil Dynamics Volume 2. American Society of Agricultural and Biological Engineers, St. Joseph, MI, pp. 1–116.

Zoz, F.M., Grisso, R.D., 2003. Traction and tractor performance, ASAE Distinguished Lecture Series Tractor Design No. 27. American Society of Agricultural Engineers, St. Joseph, MI.