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Tire rating based on soil compaction capacity

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Abstract

Compaction Capacity (CC) rating of tires presents a unique numerical CC index evaluating soil compaction risk of loaded tires. The CC rating presented here is a final product of experimental research and analysis of relations between external load and soil compaction, avoiding the intermediary role of soil stress. The research included laboratory model measurements of soil compaction by rigid round pressure plates in a cylindrical soil container. Equation for the CC index reads: $CC = 1000\ [(soil\ dry\ density/1420) - 1]$, where the number 1420 indicates the dry density of loam in kg/m^3, critical for plant growth. The CC rating takes into account the area of tire–ground contact patch and tire load, which depends on inflation pressure. If the average dry density is 10% higher than the critical dry density, the CC index equals 100. This is considered as a practical limit to ecological tire operation on cultivated crop-producing land. Agricultural tires with mean contact pressures less than 70 kPa have zero CC index. Their qualities are classified by Low Compaction Capacity (LCC) index based on 1290 kg/m^3 soil dry density. Both the CC and LCC indices do not distinguish between towed and driven wheels. The tables in this paper show how these simple indices can complement load data published by tire manufacturers.

Keywords: Off-road tires; Soil compaction; Tire rating; Compaction Capacity index

1. Introduction

The detrimental effect of excessive soil compaction on its condition and fertility has been sufficiently explored and surveyed (e.g. Soane, editor [1]). This soil compaction, showing up as an increase of soil wet density, occurs mostly when a vehicle operates on land with increased soil moisture or due to improperly dimensioned running gear of heavy field machinery, though loaded and inflated according to manufacturers' technical instructions. These load and inflation pressure specifications provide recommended combinations of tire inflation pressure and load, with respect to carcass strength and casing deflection on firm ground, however do not account for their impact on soft ground. There exists an obvious disproportion: whereas existing legal regulations restrict the load imposed on hard roads by vehicle running gear, to date there have been published only general recommendations about tire load and inflation pressure for soft agricultural ground, addressed principally to machine operators [2]. To help with the choice of tires for off-road vehicles with minimum soil compaction risk, this article offers a practical method of tire rating by means of Compaction Capacity (CC) index, which may complement the manufacturers' load – inflation pressure data.

Some of the numerous research and technical reports dealing with soil response to mechanical impact since the middle of the last century were aimed at clearing up the relations between the stress field in the ground and its compaction. For instance, Söhne has published, in addition to pressure bulbs, the valuable results of kneading tests in clay-loam soil, which have proved the increased susceptibility to compaction of this soil at around 20 % moisture content dry basis [3]. Soane and Van Ouwerkerk have edited a cluster of papers by experts on this subject (Koolen, Kuipers, Horn, Håkansson, Gupta - Raper etc. [4]). Particular attention deserves the experimentally based proposal of axle load limits 6000 kg for Swedish forestry by Håkansson

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Nomenclature

Abbreviations and definitions

AR	aspect ratio of tire section h_t/b_t
C	as subscript: referring to pressure plate C
CC or LCC index	numerical value of CC rating
CC rating	tire Compaction Capacity rating ($q_s \geqslant 70$ kPa)
CF	compaction function $\rho_d = f(z_p, q_s)$
conversion	change of CF_C into CF_X or CP_X explained in part 4.2
CP	compaction profile $\rho_d = f(z_t, q_s)$
LCC rating	tire Low Compaction Capacity rating (35 kPa $\leqslant q_s \leqslant$ 70 kPa)
modeling imprint	imprint of loaded pressure plate C into standard soil in the soil container
p	as subscript referring to laboratory soil container
SGP equation	equation for calculating tire footprint area S_T on firm ground (cm^2)
standard soil	clay loam with status defined in Section 2.1
t	as subscript referring to a tire or terrain

Symbols

b	tire footprint width on firm ground, Eq. (8) (cm)
b_t	tire section width (cm)
d_r	rim diameter (cm or inches)
d_t	tire outer diameter (cm)
h_t	tire section height, Eq. (7a) (cm)
l	tire footprint length on firm ground, Eq. (8) (cm)
r_s	tire static loaded radius (cm)
q	effective contact pressure for a tire footprint area, Eqs. (C3) and (B3) (kPa)
q_s	mean contact pressure for a round or square plate (kPa)
t_p	depth of the modeling imprint (cm)
t_t	average depth of the rut pressed by a tire (cm)
z_d	depth below the ground surface (cm)
z_p	depth below the modeling imprint (cm)
z_t	depth below the tire footprint in standard soil (cm)
S_C	area of the standard pressure plate C (cm^2)
S_P	area of an arbitrary pressure plate (cm^2)
S_T	footprint (contact) area of a tire (cm^2)
ρ_d	soil dry density (the weight of solids per unit of total volume of soil mass, kg/m^3)
ρ_{dl}	standard soil dry density 1420 kg/m^3 for the CC rating
ρ_{dL}	reference soil dry density 1290 kg/m^3 for the LCC rating
ρ_{dm}	maximum dry density of standard soil at 93% saturation with water (kg/m^3)
ρ_{do}	dry density at zero depth z_p or z_t (kg/m^3)
ρ_{ds}	average dry density in the depth range z_d = 20 to 50 cm (kg/m^3)
ρ_r	relative dry density equal to ($\rho_d - \rho_{dl}$ or $\rho_d - \rho_{dL}$) (kg/m^3)

[5]. The specialized VDI guidelines [6] brought practical, scientifically founded advices to machine operators how to dispose of soft ground.

Terramechanics is a technical branch developed particularly to study the interaction of a moving body with soft ground. Typically, the research in this field requires experiments in soft soil and their analysis to get conclusive results. The theoretical soil mechanics, originally developed for purposes of civil engineering (e.g. design of foundations, dams, etc.), has particularly been available as a tool for this research. This explains why the mechanical impact of running gear on soft ground was studied and expressed in terms of soil stresses in hope that it will be possible to define the link between the stress field as cause and soil compaction (three-dimensional strain) as the consequence. A sophisticated attempt of compaction modeling in this sense was for example reported by Bailey et al. [7]. Concerning the stresses, Söhne succeeded to visualize the expected isobaric lines in ideal soil under the tire footprint for three levels of soil moisture content [3,8] by applying the Fröhlich's civil engineering stress concept [9]. These lines became popular as pressure bulbs and due to their comprehensiveness found good use at least in education. Up to the present day, the development of the envisaged soil stress – compaction theory has proved unfeasible due to extreme complexity of the case and uncertain correlation between the stress state and compaction of different soil textures [[10, Section 19.29].

At present we observe a rapid development of computer technologies and methods including the generally applicable finite element modeling. Promising contributions in this respect exist also in the discussed field, for example the article by Xia [11], which demonstrates the form and some effects of a virtual tire on soft virtual ground. In general,