Farmland protection by means of tyre load rating

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Abstract: At present, the professionals in the industry and farming still miss comparative technical data indicating the potential of agricultural vehicles and mobile machinery to inflict compaction damage upon the cultivated soil. Harmful compaction means especially the increase of soil bulk density above a critical level required for efficient plant production. In general, it seems reasonable to restrict the excessive soil compaction by loaded wheels starting from the design of farm power and machinery, which means to provide technical data on the compaction potential of tyres. This paper presents the technique of tyre rating by means of the index Compaction Capacity (*CC*), which simply reflects the compaction potential of any individual tyre contained in a tyre catalogue within the whole range of loads and inflation pressures.

Keywords: agricultural tyres; soil compaction modelling; compaction capacity; tyre rating

Tyres of agricultural machinery and vehicles may cause serious compaction damage to farmland even if they are properly inflated according to the data of ETRTO and tyre manufactures, because such data are based on tyre properties on firm surface. For instance, the common clay loam soil with dry bulk density exceeding the critical value ρ_{dl} = 1420 kg/m^3 has been specified as harmfully compacted by experienced soil scientist Dr. Lhotský (in Grečenko 2003). Here arises, indeed, the technical problem of how great can be a tyre load, which would avoid such compaction? Most of the research and technical literature since the fifties of the last century was dealing with the stresses within the ground as visualized by the popular pressure bulbs referred by Söhne (1958), which, however, have no direct relation to soil compaction. Several scientific attempts to establish the stress – compaction relationship in the soil were made by different researchers since the eighties, unfortunately still inadequate for practical use (Bailey *et al.* 1992).

A logical solution of the mentioned inadequacy is to relate the soil compaction directly to the acting tyre load avoiding the stresses. This can in principle be achieved by means of laboratory compaction experiments under controlled conditions. The first author of this paper has contemplated such a possibility since the early nineties of the past century when working as a leading team-member on a state sponsored research program on soil compaction by heavily loaded wheels of agricultural trailers in field conditions, which was subsequently modelled in the laboratory of the Technical faculty of the Czech University of Agriculture in Prague (Grečenko *et al.* 1997). This program has corroborated the idea that physical modelling can predict full-scale ground compaction.

The presented paper is based on the principal study of this problem by Grečenko (2003), which deals with the history, laboratory equipment, evaluation of the problem, fundamental theory and scenario of laboratory model experiments. The series of experiments, leading to a databank of soil dry bulk densities as a function of depth below the centre of a loading device (so called compaction functions) and their processing into the presented exemplary tyre *CC* ratings, was carried out in the years 2005 and 2006. The first author has carried out the labora-

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tory measurements necessary to set up the databank of compaction functions and performed the *CC* evaluation of presented tyres using the system and technique of *CC* rating evaluation worked out by the second author.

MATERIALS AND METHODS

Compaction capacity of off-road tyres

Compaction capacity (*CC*) rating is a dimensionless number (referring to soft ground), assigned to complement each inflation pressure – load combination listed in tyre catalogues (referring to hard ground). *CC* rating is computed from the same formula Eq. (1) as the earlier *CN* [Compaction Number (Grečenko 2003) – change to *CC* for technical reasons]:

$$CC = 1000\ [(\rho_{ds}/\rho_{dl}) - 1]\ (‰) \quad (1)$$

with

$$\rho_{ds} = ¼\ (\rho_{d20} + \rho_{d30} + \rho_{d40} + \rho_{d50}) \quad (2)$$

where:

ρ_{dl} – critical value of the dry bulk density

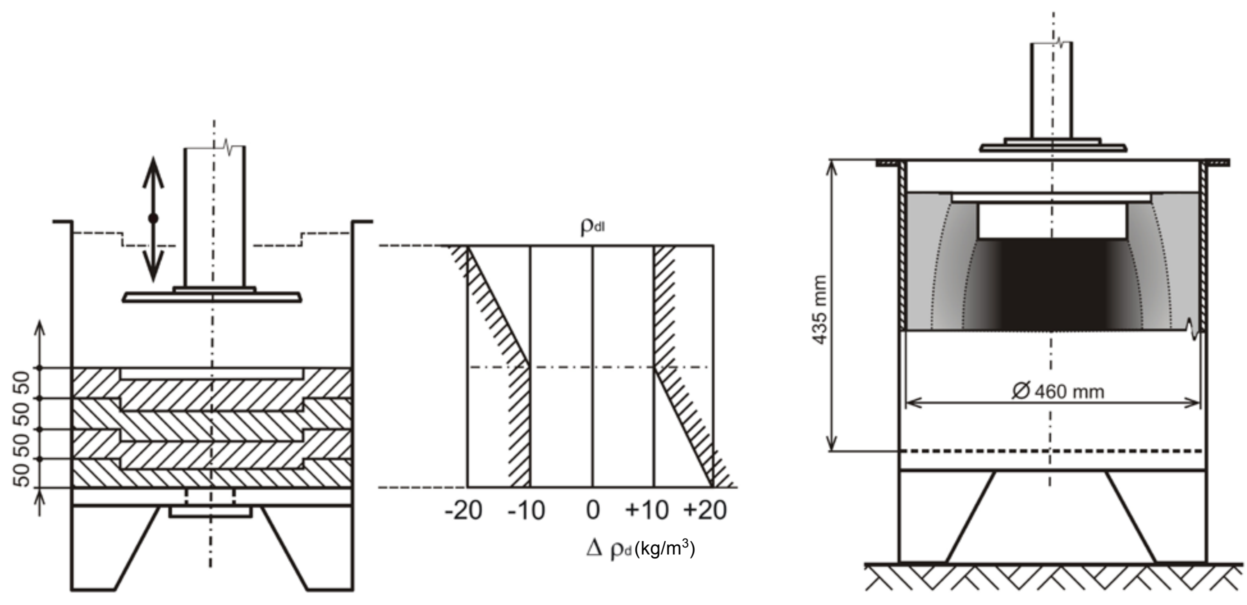
ρ_{ds} – average value from four ρ_d readings at the depths 20, 30, 40, 50 cm below field surface

An inflation pressure – load combination with $CC \leq 0$ would rate as soil friendly, whereas $CC = 100$ (meaning that the average soil bulk density in the mentioned range of depths is 10% above the critical bulk density) may present a conventional upper limit for field operation of a tyre.

Principles of soil compaction modelling

Imagine a deep homogeneous soil layer at the state of critical density. A sufficiently loaded wheel with tyre will produce a rut of a depth t_1 at the first wheeling. Every consecutive wheeling will deepen this rut due to reduced contact area. At the fourth wheeling the rut of the depth t_4 will be practically completed, i.e. rigid at the bottom (smallest contact area S_4, greatest contact pressure q_4), and the soil compaction (increase of bulk density) underneath reach its maximum.

A rigid plate with equal contact area S_4 and contact pressure q_4 is capable to penetrate to the same depth t_4 and to inflict a corresponding compaction. This case can be modeled in the testing soil bin filled by the same precompacted soil using a round pressure plate of smaller size S_p, however loaded to the same contact pressure q_4. The resulting smaller depth of impression would produce a soil compaction pattern reduced in size and depth. This mechanism was duly studied and in the meantime is well understood enabling to introduce a reverse procedure: a modelled compaction function can be converted into a compaction profile under a full-size tyre, which has an equal mean contact pressure as the pressure plate.



(a) (b)

Figure 1. Scheme of testing soil bin: (a) filling and precompacting the charge, (b) situation after the modelling imprint

Several comments:

– the compaction is determined in the soil column under the centre of a tyre or pressure plate contact area;
– a round pressure plate can model a nearly round or square form of a tyre imprint; some correction of contact pressure is, however, necessary if the tyre imprint is oval or rectangular;
– the flat surface of a steel pressure plate is compatible with the flat interface of a tyre properly loaded and inflated on firm bottom of a rut regarding the soil compaction effect.

Outline of the compactor modelling technique

The soil used in laboratory tests was the Suchdol loam (Grečenko *et al.* 1997; Grečenko 2003), sensitive to compaction when sufficiently moist, which is classified as clay loam or loam in the USDA textural triangle due to its location on the boundary. Its critical dry bulk density is 1420 kg/m^3. The *CC* rating values based on this soil can be used for other soil types if necessary after some adjustments of critical dry bulk density and the *CC* limit; for example, on a sandy soil the maximum *CC* rating could be higher, on a clay soil lower than the conventional 100.

The testing soil bin of the laboratory compactor has a usable volume of 0.072 m^3. In the performed experiments, the soil charge in the bin was first precompacted by a large round compacting plate to the vertically homogeneous critical bulk density (Figure 1a) and then loaded by a selected pressure plate with desired mean contact pressure to produce the modelling imprint (Figure 1b). The bulk density profile along the centre of the soil column, called compaction function in dried out condition, was then established by taking samples, which afterwards were dried out in an oven. The soil dry bulk density values for different contact pressures were fed into the databank and used afterwards as inputs for computing the soil compaction profile (i.e. dry bulk density against the full size depth bellow the ground surface respecting the depth of rut) under an evaluated tyre.

To produce a valid databank of compacted dry density values it was necessary to observe the following rules:

(a) every soil charge was moistened to the prescribed moisture content between 85 and 90% of the Atterberg plastic limit (from 22 to 23% moisture content for the Suchdol loam), when the soil was very compactable, and then left 48 h to stabilize without evaporation before being filled into the testing soil bin;

(b) the soil charge in the testing soil bin was precompacted by layers to the critical dry bulk density ρ_{dl} in order to become practically homogeneous throughout the height of the soil column (Figure 2). The required precompaction corridor was achieved by applying different generating pressures for individual layers, since every successive compaction affected all the layers underneath;

(c) the modelling imprint lasted 15 seconds.

The conditions and technique of evaluating the *CC* rating of a tyre through conversion of the databank of compaction functions are as follows:

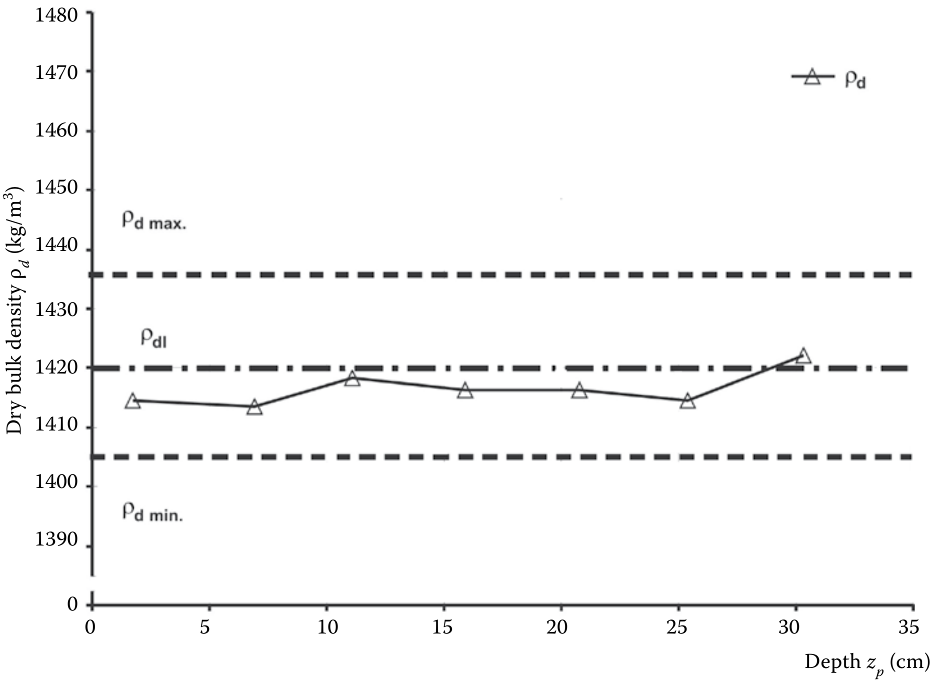


Figure 2. Example of soil precompaction satisfying dry bulk density corridor

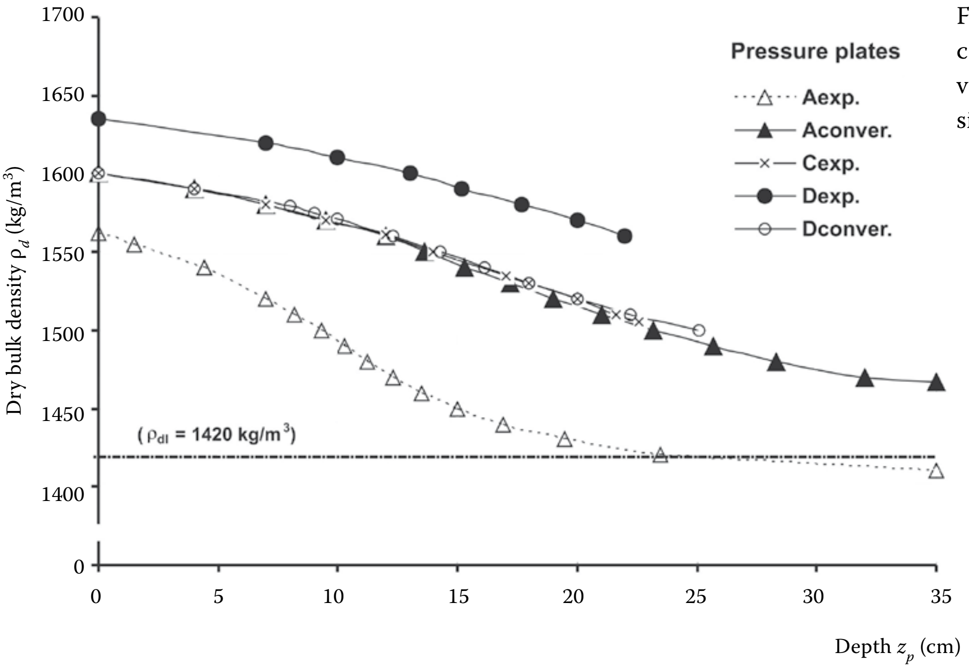


Figure 3. Example of soil compaction profiles with verification of the conversion procedure

(a) the following inputs are required:
circumferential footprint area of a tyre on a firm, flat and smooth surface, best of all by a multiple imprint technique, for a given inflation pressure and loading;
(b) maximum length and width of this footprint area; the *CC* rating respects the shape of the contact patch;
(c) the conversion of a proper compaction function to the compaction profile of a tyre consists of several steps and respects among others the effect of the ratio of respective contact areas and the difference between the rut depths tyre – pressure plate. The theorems based on the theoretical soil mechanics have been found useful (Grečenko 2003).

The verification of the conversion process

An example of this verification is shown in Figure 3. The problem was whether and how it would have been possible to convert the compaction functions measured with the pressure plates A and D at a specified mean contact pressure into the compaction functions measured with the plate C (A is smaller than C; D is larger than C). The positive outcome of this verification enabled to work out a reverse procedure, namely to predict the compaction function of an evaluated tyre using the databank of laboratory measurements and thus to determine the four important dry bulk density values of a tyre compaction profile, which are required to calculate its *CC* rating.

Examples of *CC* rating

The application of *CC* rating is demonstrated on five tyre sizes in Table 1. The respective values of tyre contact areas are as follows:
(1) 12.5/80-18 (10 PR, S_t = 1110 cm^2) agricultural machinery, driving;
(2) 14.5/80-18 (12 PR, S_t = 926 cm^2) heavy-duty trailers;
(3) 9.5-24 (6 PR, S_t = 530 cm^2) tractor, driving;
(4) 14.9-28 (6 PR, S_t = 1395 cm^2) tractor, driving;
(5) 38×20.00-16.1 (8 PR, S_t = 1495 cm^2) agricultural machinery, driving.

Considering the value of *CC* = 100 up to 110 as an upper limit, both the tyres for agricultural machinery (1), (5) and the tractor larger tyre (4) display a favourable *CC* rating, the tractor smaller tyre (3) has an excellent negative *CC* rating (however, decisive for tractor application would be the higher value from both axles), while the trailer tyre (2) has a recommended load limit of about 3010 kg at 300 kPa inflation pressure on soft ground.

CONCLUSION

The soil compaction capacity (*CC*) rating of tyres has been developed as an engineering technique based on laboratory model soil compaction measurements using the Suchdol loam soil with textural classification on the boundary between loam – clay loam (after USDA). The goal of the *CC* rating is to provide a comprehensive and credible technical information about the soil compaction inflicted

Table 1. *CC* rating complements the catalogue data (inflation pressure *p* (kPa) and tyre load Q_m (kg)) of selected agricultural tyres

12.5/80-18 (10 PR)			14.5/80-18 (12 PR)			9.5-24 (6 PR)			14.9-28 (6 PR)			38×20.00-16.1 (8 PR)		
p (kPa)	Q_m (kg)	*CC*	*p* (kPa)	Q_m (kg)	*CC*	*p* (kPa)	Q_m (kg)	*CC*	*p* (kPa)	Q_m (kg)	*CC*	*p* (kPa)	Q_m (kg)	*CC*
100	1180	37	150	2035	72	80	525	–32	80	1195	57	35	680	24
150	1485	51	200	2365	84	100	600	–26	100	1335	64	70	1030	50
175	1640	58	250	2690	95	110	640	–24	110	1405	68	105	1300	67
200	1790	65	300	3010	106	130	710	–18	130	1545	73	140	1540	81
225	1940	72	325	3175	110	140	740	–16	140	1610	76	175	1760	86
250	2090	79	350	3330	113	160	800	–12						
275	2235	87	375	3495	117	170	830	–10						
300	2375	91	400	3660	121	180	860	–8						
			425	3850	126	200	910	–4						
						210	940	–1						

by a loaded tyre, operating on cultivated ground, within the range of 20 to 50 cm depth below the field surface in terms of a single dimensionless number. The established databank of compaction functions enables to predict the compaction profiles (basis of *CC* rating) under evaluated tyres using the soil mechanics and new own findings.

Actually it is possible to evaluate the *CC* rating of any tyre from these data:
– inflation pressure and load,
– circumferential area of the tyre contact patch on a firm, flat and smooth surface,
– principal dimensions of the contact patch: maximum length and width.

The authors believe that this rating, included into the tyre data catalogues, can help the industry and farmers to select the best tyre outfit for tractors and machinery. The *CC* rating offers an objective comparison among several tyres considered in a project (the machine equipped with lower *CC* tyres may be more expensive, however enable a higher production output) based on assessment of the absolute value of expected soil compaction. For instance, *CC* = 80 means that the average dry bulk density in the ground layer between 20 and 50 cm below the field surface can exceed, under moist conditions, the critical value 1420 kg/m^3 by 8%. It is possible, indeed, to determine the complete compaction profile in the ground under the tyre, i.e. the dry bulk density of a homogeneous soil as a function of the depth below the field surface.

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Abstrakt

Prikner P., Grečenko A. (2007): **Ochrana zemědělské půdy prostřednictvím ratingu zatížené pneumatiky**. Res. Agr. Eng., **53**: 8–13.

V současné době odborná veřejnost v průmyslu i zemědělství stále postrádá poměrná technická data, vyjadřující potenciál pojezdového ústrojí zemědělských vozidel a strojů způsobit škodlivé zhutnění na obdělávané půdě. Škodlivé zhutnění znamená především zvýšení objemové hmotnosti půdy nad kritickou úroveň, požadovanou pro efektivní rostlinnou výrobu. Je nutné omezit nadměrné zhutnění půdy zatíženými koly; je třeba začít konstrukcí zemědělské techniky a strojů, což znamená nutnost poskytnout technické údaje o kompakčním potenciálu pneumatik. Článek prezentuje metodu ratingu pneumatiky prostřednictvím indexu kompakční kapacity (*CC*), která jednoduše vyjadřuje kompakční potenciál jakékoli individuální pneumatiky, zahrnuté v katalogu pneumatik, v maximálním rozsahu zatížení a tlaků huštění.

Klíčová slova: zemědělské pneumatiky; modelování utužení půdy; kompakční kapacita; rating pneumatiky

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