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Research Paper

Soil rut depth prediction based on soil strength measurements on typical Estonian soils

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Deep ruts in soil hinder the movement of off-road vehicles and harm drastically the soil environment. The aim of this study was to determine the most suitable cone and remoulding index based methods for rut depth estimation for single and repeated military vehicle passage in typical Estonian soils. Cone index based sinkage models – US Army ERDC, Maclaurin (1990) and Willoughby and Turnage sinkage models applicable for military vehicles were tested, using different critical layers (0–15 cm, 7.5–23 cm or 15–30 cm). The test vehicles were a 7 Mg truck and a 23 Mg armoured personnel carrier. At eight experimental sites covering mechanically very variable soil conditions (from peat to clay soil), rut depth was measured after one and ten vehicle passes, cone penetration tests were conducted in situ, and samples were collected for determination of bulk density, organic carbon content, texture, gravimetric water content, plastic and liquid limits of the topsoil and subsoil. According to average RMSD values for military truck the Willoughby and Turnage model was the most accurate prediction method. For one pass and 10 passes the rating cone index values from the 7.5–23 cm and 15–30 cm soil layer, respectively, produced the lowest RMSD values.

1. Introduction

Besides the machinery traffic on forestry or agriculture lands, the military vehicles have certain needs to move off-road. The interactions between vehicle and soil produce ruts with variable depths. Ruts cause the negative and long-lasting influence on soil structure; the consequences of deep ruts include higher fuel consumption and lower travel speed for vehicles. Thus, ruts can reduce vehicle trafficability, i.e. the ability of vehicles to traverse a particular terrain. In the worst cases, deep ruts can cause vehicle immobilisation. Vehicle immobilisation is defined as a condition in which the vehicle

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Nomenclature

δ	tyre deflection, m
a	multi-pass coefficient
b	tyre unloaded width, m
BD	bulk density, Mg m^{-3}
BD_{rel}	relative bulk density
CI	cone index, Pa
d	tyre unloaded diameter, m
h	tyre unloaded section height, m
LL	liquid limit
N	number of passes
N_C	ERDC (US Army Engineer Research and Development Centre) wheel clay numeric
N_{CI}	Turnage wheel numeric
N_{CZ}	variant of the ERDC wheel clay numeric
N_S	ERDC (US Army Engineer Research and Development Centre) wheel sand numeric
SOM	soil organic matter content
PI	plasticity index
PL	plastic limit
RI	remoulding index
RCI	rating cone index, Pa
SOC	soil organic carbon content
s	wheel slip
z	wheel sinkage, m
z_1	sinkage after one pass, m
z_n	sinkage after n pass, m
z_p	powered wheel sinkage, m
w	gravimetric water content
W	wheel load, N

passage-induced rut depth is larger than the vehicle clearance height (Affleck, 2005). Predictions of rut depth and vehicle immobilisation are required for planning purposes, i.e., for decisions regarding alternative routes or selecting suitable vehicles for a particular terrain (Herl, Doe, & Jones, 2005). Due to their assignments, military vehicles often have to move many times in the same track; therefore, the effect of repeated traffic on rut depth must be taken into account.

The ruts and associated soil compression caused by vehicle passage are dependent on soil properties (such as texture, moisture, organic matter content and disturbed or undisturbed soil state) and vehicle parameters including vehicle load, tyre size, inflation pressure and the number of passes (Bekker, 1960; Botta, Jorajuria, Rosatto, & Ferrero, 2006; Raper, 2005). Liu, Ayers, Howard, and Anderson (2010) showed that military vehicle type, soil moisture and soil texture affect rut formation. Soil water content has a crucial role in rut formation. Generally, wetter soils are more susceptible to soil compaction (Horn & Fleige, 2003). Raper (2005) revealed that the greatest compaction occurs when soil is loaded at soil moisture conditions close to field capacity. According to Lal and Shukla (2004), soil is most susceptible to compaction when its moisture content is around the plastic limit and possesses the lowest shear strength if the soil is in a liquid state. Additionally, they stated that in soils with organic matter content of less than 5%, the increase of organic matter increases the plastic and liquid limits. Hence, soil texture, organic matter content, soil moisture and cultivated or uncultivated state are recognised as the main determining factors for rut formation and are taken under consideration in this study.

Soil compressibility depends on soil bearing capacity, i.e., soil capability to withstand exerted stresses. Soil bearing capacity is often obtained from cone index (CI) values determined with a cone penetrometer. Hemmat, Yaghoubi-Taskoh, Masoumi, and Mosaddeghi (2014) showed that CI can be used as soil trafficability criteria. Throughout the years, a large number of cone index based empirical models have been developed for prediction of drawbar pull, soil thrust, motion resistance or rut depth (Taheri, Sandu, Taheri, Pinto, & Gorsich, 2015). Cone index related rut depth models have been developed by different authors based on vehicle type or soil type (Pirnazarov, Wijekoon, Sellgren, Löfgren, & Andersson, 2012; Saarilahti, 2002).

As the American Society of Agricultural Engineers (ASAE) standard, a 30° cone with a base area of 3.23 cm^2 is forced vertically through the soil, and the force per cone area (expressed as penetrometer resistance in units of Pa or psi) is called cone index (CI). Because the soil strength can decrease or increase after passing the first wheel of the vehicle over the soil, a parameter called remoulding index (RI) is introduced in trafficability studies. For RI determination the undisturbed soil sample is obtained with a piston-type soil sampler and deposited into a cylinder mounted on a steel base. CI values are measured before applying 100 blows with a 1.13 kg hammer and after 100 blows. RI is calculated as the sum of CI readings after remoulding divided by the sum of CI readings before remoulding (Priddy & Willoughby, 2006). The CI value is multiplied with RI, and this corresponding parameter is called rating cone index (RCI) (Wong, 2008). The biggest advantage of using the cone penetrometer is the quick estimation of trafficability. However, CI and RCI values have spatial variabilities, even within a small area. Previous studies have shown that CI and RCI values obtained for a visually homogeneous area may indicate strength states that correspond to contradictory situations: easily trafficable as well as not passable at all.

The concept of a critical layer is used to account for vertical soil strength variability. According to the ISTVS Standards (1997), the critical layer is the layer that is the most significant in terms of trafficability. Most commonly in trafficability studies for military vehicles simple go or no-go estimation of 15–30 cm layer as the critical layer is used. But depending on soil type, vehicle weight, number of passes the critical layer can also be 0–15 cm or 7.5–23 cm. For extra heavy wheeled vehicles, wheel load over 4536 kg, the critical layer is 23–38 cm (FM 5-430-00-1, 1994; Priddy & Willoughby, 2006; Wong, 2008). In traction studies, the depth of the critical layer is dependent on the magnitude of wheel sinkage (Wismer & Luth, 1974). The high variability of soil strength in a soil profile and the fact that there is no uniquely accepted critical depth complicates the numerical prognoses of trafficability in the field prior to trafficking.

In the following, we review some widely used models for prediction of rut depth caused by military vehicles. The US