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Reduced testing and modelling of the bearing capacity of rooted soil for wheeled forestry machines

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Abstract

The next generation of forestry machines must be developed to be gentler to soil and to the root mat than present machines, especially in thinning operations. The bearing capacity of the soil is a key property for determining the terrain trafficability and machine mobility. This asks for better and more general terramechanics models that can be used to predict the interaction between different machine concepts and real and complex forest soil.

This paper presents results from terramechanics experiments of rooted soil with a new and small-scale testing device. The force–deflection results are analyzed and compared with analytical root reinforcement models found in literature. The presented study indicates that rooted soil properties obtained with the new laboratory test device can be used to create an augmented soil model that can be used to predict the bearing capacity of rooted soil and also to be used in dynamic machine–soil interaction simulations.

Keywords: Bearing capacity; Forest soil; Root reinforcement; Shear resistance

1. Introduction

Sustainable forest management requires more gentle techniques and technologies that have less negative impact on the environment in thinning operations where there is removal of trees in order to regulate stand density for an improved growth rate. During the last decades, quite a large number of mechanized and computerized forest machines have been launched to the market to increase the harvesting and log transportation productivity. These machines are heavy, e.g. the machine mass of a large harvester can be more than 20 tons giving at a total mass of 40 tons for a fully loaded forwarder. These machines are productive, from a harvesting operation point of view, but they cause soil disturbances, such as compaction and rutting (see Fig. 1).

A major disadvantage caused by machine traffic in thinning operations is the damage caused to the tree roots which reduces the growth rate of the remaining trees and also to quality losses (Wasterlund, 1990; Wronski and Murphy, 1994; Cofie, 2001; Eliasson, 2005). Trees growing close to the harvesting routes show a decreased growth rate if the machine–soil contact pressure is above 60–90 kPa. Shear stress from wheel slippage also contribute to soil damage and root breakage (Wästerlund, 1989). In addition, the fuel consumption is increased in operation on soft soil, due to larger wheels slippage and sinkage than on hard ground. The fuel consumption has a direct influence on the total cost of operation and indirectly on the level of the exhaust emissions. Therefore, models that enable prediction of the bearing capacity of forest soil is a key factor for enabling introduction of means to reduce the

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Nomenclature

A	shear plane area [m^2]	RAR	root area ratio [1]
A_r	root cross-section area [m^2]	ΔS	soil reinforcement by roots [kPa]
b	width of loading surface [m]	T	tensile strength of the root [MPa]
c	soft soil cohesion [kPa]	t	mobilized tensile strength [MPa]
d	root diameter [m]	z	thickness of shear zone [m]
f	the coefficient of friction between the root and soil [1]	τ_r	root shear stress [MPa]
E	root Young's modulus [kPa]	σ_r	normal stress in root [MPa]
h_r	depth below ground surface [m]	θ	the angle of inclination [deg]
L	root length [m]	$\varnothing$	internal friction angle [deg]
n	number of roots [1]	τ_b	the bond stress [kPa]
N_c, $N_\varnothing$, N_γ	soil bearing coefficient [1]	γ_r	soil weight density [N/m^3]
S	root permeated soil shear stress [kPa]	τ	soft soil shear stress [kPa]
P	wheel–soil pressure [kPa]	σ	compressive pre-stress [kPa]
Q	ultimate soil bearing capacity [kPa]	x	shear displacement [m]
Q_r	ultimate bearing capacity the root permeated soil [kPa]		

environmental impact, increase the productivity, and enhance the quality of thinning operations.

Wästerlund (1989) observed that the typical Swedish forest soil is podzolised and covered with a 3–10 cm thick humus layer. The soil is most commonly sandy tilt soil, which is more or less like well-graded loamy sand. The climate is humid and rather cold, so the soil is often quite wet. Sandy soil, with buried gravel and boulders, a humus layer, tree and ground vegetation roots are the most common components that together determine the strength of the forest floor.

Depending on their basic three-dimensional form, tree root systems are commonly categorized into the three groups; heart, plate, and tap systems. Most tree root systems are localized in the heart and plate systems where the total number of tree roots may be 60–120 roots m^{-2}. Roughly 70% of these roots are found in the humus layer in thinning operation stands. Less than 7% of them are larger than 10 mm in diameter (Wästerlund, 1989).

Fig. 1. Example of rutting caused by forwarder traffic in wet terrain and/or in wet seasons.

The mechanical effect of roots is widely recognized and is considered an important factor that increases the shear resistance of soft soil. The quantity and distribution of tree roots as well as their tensile strength have a great influence on the shear resistance of root-permeated soil. Thus, to be able to model the bearing capacity of forest soil, also considering the effects of the tree roots, it is crucial to have a thorough understanding of the contribution of the root reinforcement. This contribution can be described using standard plane and circular failure models commonly applied by Geotechnical Engineers. Such models usually rely on the theory of reinforced earth, which describes how tree roots enhance the shear strength of a soil mass through an increase in the apparent cohesion of the soil (O'Loughlin, 1974; Wu et al., 1976; Waldron, 1977).

The mechanical properties of root-permeated soil can examined by in-situ shear test (Ziemer et al., 1981; Wu and Watson, 1998; Fan and Chih-Feng, 2008). An in-situ experiment requires special preparation and it is generally not repeatable, i.e. it will not always give quantitatively correct results. Several reduced laboratory experiments on the quantitative effects of soil reinforcement by different configurations of roots have been reported, e.g. (Gray and Ohashi, 1983; Abe and Ziemer, 1991; Mickovski et al., 2009). As the shearing condition under a wheel is slightly different than in a sloped terrain subjected to gravity forces, slope stability models that take root reinforcement into account cannot be directly used for predicting terrain trafficability and machine mobility.

Thus, the general aim of the presented research is to study tree contribution to the soil bearing capacity from roots, and to predict the soil shear stress for wheeled ground vehicles operating on soft rooted soil. The specific task of this paper is to find and present answers to the following research questions: