Forest Machine Tire-Soil Interaction

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Abstract:
New forest machine solutions have to be much gentler to the ground than today's machines. To be able to develop a forestry machine that preserves the terrain requires a proper understanding of the interaction between tire and soil. The purpose of this study was to contribute to the existing knowledge of forest machine tire-soil interaction. A comparison of analytical results from different WES-based terrain interaction modelswith full-scale field test results is presented. A Valmet 860.3 Adams-MBS model, developed at KTH, was modified to simulate the effects from soft-soil. Results from model simulations were compared with analytical WES-based methods.

Keywords: Forestry machines, Soil damage, Tire-soft soil simulation, WES

1 Introduction

The most predominant method for forest harvesting in Sweden is the cut-to-length (CTL) method. It is based on two-machines, a harvester that fells the trees and cut them in a predefined length, and a forwarder which transports the logs to a landing area for further transport to a processing facility. Forestry machine design has improved significantly in recent years. Off-road vehicle research and development has been successfully applied in the development process of the new generation of forestry vehicles.

North European forest soil is a very complicated and sensitive bed and it has very little resemblance with typical agricultural soils. It consists of large areas of sand and clay with embedded stones and rocks of various sizes and with several root layers that significantly contribute to the bearing capacity. Large areas are also marshland with very low bearing capacity. Furthermore, in thinning operations, due to tree growth rate considerations, the root layers must also be protected from breaking. Wheeled vehicles are typically more agile and maneuverable than tracked vehicles, but the drawback is that they give higher ground pressures and thus larger rutting causing more damage to the roots. Consequently, analyses of the bearing capacity of soils and vehicle mobility prerequisites proper methods to model and simulate forest machine-terrain interaction.

Vehicle-terrain interaction covers issues such as tire-soil friction, rutting, soil compaction, traction and rolling resistance. The wheel rut depth is one of the key factors to determine vehicle performance and energy consumption and the damages caused to ground and vegetation. Measurement and characterization of the mechanical properties of a multilayer soil that may efficiently be used for mobility predictions is a complex task. The two predominant techniques to determine the mechanical properties of the soil arethe Cone penetrometer and the Bevameter techniques. The Bevameter technique is comparatively less efficient for characterizing non homogeneous soils, such as typical Nordic forestry soil. The widely used WES-method is a set of semi-empirical methods that are based on Cone-penetrometer data to describe soil mechanical properties and to model wheel-soil interaction and to predict mobility and trafficability. Studies on tire-soil interaction are numerous ranging from pure empirical methods through semi empirical and theoretical ones (Löfgren 1992). Choice ofthe most appropriate model is very much determined by the objectives of the study, e.g. to optimize a machine or to determine whether a machine is capable of negotiating a particular area of terrain. When selecting a model,careful attention needs to be paid to the inherent limitations in eachmodel.

1.1 The cone-penetrometer index

Cone index (CI) is a soil mechanical property that is widely used to assess soil strength in design of off-road vehicles. CI has beenused successfully by the U.S. Army Engineer Waterways Experiment Station (WES) as a descriptor of soil strength to establish empirical soil-vehicle relations for predicting the performance of ground-crawling vehicles. CI is a measure of the resistance of the soil to the penetration of a right-circular cone. CI is measured in force per area. Recent developments in analytical modeling of vehicle performance require that the soil can be described in terms of its fundamental properties such as angle of internal friction, cohesion, stiffness, density, etc. In order to utilize the large CI database and establish correspondence between the empirical studies and theoretical mobility models, it was necessary to correlate CI with the engineering properties of soil (Behzad et al. 1981).

Soil compaction begins to inhibit the root growth of most plants when the soil's strength is about 1500 kPa. The roots of many plants quit growing when the soil's strength reaches about 2500 kPa. Penetrometer tests can help identify these areas faster and easier than standard bulk density tests (Kees 2005). Soil moisture is an important factor which significantly affects the soil CI. Typically, drier soils have higher CI values. Busscher and Ohu found a relationship between CI and moisture of soils (Kumar et al. 2012).

1.2 Soil bearing capacity

The soil bearing capacity is the ability of the soil to safely carry the pressure placed on the soil from any vehicles. The soil bearing capacity is related directly to soil penetration resistance in the WES-method. Thus, a soil's CI can be considered as an indicator of its bearing capacity.

In soil engineering, the sinkage of the footing(wheel or track) is used as an output variable, and different soil bearing models are developed using different soil parameters as input variables (Saarilahti 2002). The main cause of soil compaction is soil sinkage imposed by a wheel or track. Therefore, prediction of soil sinkage is incredibly important for determining the level of soil compaction. For the last five decades, prediction of soil sinkage has been of great interest to agriculture as well as cross country mobility researchers.

The relation between wheel sinkage and contact pressure is reflected in the following equation:

$$\mathrm{P} = \mathrm{kZ} \qquad (1)$$

where P is contact pressure(kPa); k is soil deformation modulus and Z is wheel sinkage (m). Bekkerintroduced an assumption of a relation between pressure and sinkage for mineral terrain, including an exponent depending on the soil type (Wong 2010):

$$\mathrm{P} = \left(\frac{\mathrm{k_c}}{\mathrm{b}_p} + \mathrm{k}_\emptyset\right)\mathrm{Z}^\mathrm{n} \qquad (2)$$

Where, n; $\mathrm{k_c}$; $\mathrm{k}_\emptyset$are pressure-sinkage parameters; $b_p$is radius of a circular place (m).

Influenced by the work of a more fundamental nature in soil mechanics and by experimental evidence, Reece proposed the following equation for the pressure-sinkage relationship for homogeneous soil (Wong 2010):

$$\mathrm{P} = \left(\mathrm{ck}_\mathrm{c}' + \gamma_\mathrm{s}\mathrm{bk}_\emptyset'\right)\left(\frac{\mathrm{z}}{\mathrm{b}}\right)^\mathrm{n} \qquad (3)$$

Where k_c'; $\mathrm{k}_\emptyset'$are pressure sinkage parameters; c is the cohesion ofthe terrain; b is radius of a circular plate (m); γ_s is the weight density of the terrain.

Because the soil bearing capacity is largely dependent on soil cohesion and soil internal friction, bearing capacity analysis requires a distinction between cohesive and non-cohesion soils. Cohesive soils are fine-grained materials consisting of silt, clay, and/or organic material. Non-cohesion soil is composed of granular or coarse-grained materials with visually detectable particles and with little cohesion or adhesion between the particles. These soils have little or no strength, particularly when dry and unconfined, and little or no cohesion when submerged. Strength occurs from internal friction when the material is confined.Apparent adhesion between particles in cohesionless soil may occur from capillary tension in the pore water. Cohesionless soils are usuallyrelatively free-draining compared with cohesive soils.

As the soil bearing capacity is dependent on soil cohesion and internal friction of soil, Saarilahti (2002) considers that the contact pressure can be twice the soil cohesion:

$$Q_u = 2 \cdot c \quad (4)$$

The resistance to penetration of a soil is related to soil moisture properties and organic matter content. The higher the moisture content of the soil the lower the resistance to penetration and hence the bearing capacity. A higher organic matter content positively affects the bearing capacity.

As soil cohesion is closely linked to soil water content. If soil water content increases, the soil capacity also directly decreases and soil damages, such as soil compaction, rutting, and displacement occur.

1.3 Soil texture

Soil texture is a characteristic soil parameter that drives forest field management. The soil textural class is determined by the percentage of sand, siltand clay. Soils can be classified in four different textural classes: sand, silt, loam, and clay.

A typical Swedish forest soil is podzolised and covered with a 3-10 cm thick humus layer. The soil is often a glacial deposit. Most common is a sandy soil which is more or less like well-graded loamy sand. Boulders are quite common. Since the climate is humid and rather cold, the soil is often quite wet. A sandy soil with gravel and boulders, a humus layer, tree roots and ground vegetation roots are most likely to be the main components determining the strength of the forest floor (Wästerlund 1989). Soil strength is largely controlled by the soil texture and water content. In general, soil strength decreases as soil textures become finer. Soils with low strength are more susceptible to compaction and related disturbances.

1.3.1 Soil compaction

Compaction of forestry soils is one of the main causes of soil degradation and it negatively affects all soil properties. The susceptibility of a soil to compaction depends primarily on its physical-mechanical properties, which depend on soil type and water content. Soil compaction reduces the volume and pore space. These pores the spaces between soil particles are filled with water and air. The heavy equipment used in CTL compacts the soil and can dramatically reduce the amount of pore space. This compaction not only inhibits root growth and penetration but also decreases oxygen content in the soil that is essential for the growth and function of the roots.

The compression of soil pores also can limit root growth by making it more difficult for growing root tips(Allan et al. 2002). Mouazen (2002) performed tests in order to study the mechanical behavior of the upper layers of a sandy loam soil under shear loading and those tests showed an increased density.

1.4 Rutting

Rutting of forest soils is defined as the destruction of soil structure caused by a deformation of the soil surface. Soil rutting occurs when a downward pressure exerted on the wet soil exceeds its shear strength and causes failure. As the water content of a soil approaches saturation, the compatibility decreases because the air spaces are filled with water, but the potential for rutting increases. In the general case, rutting is accompanied by compaction, e.g. along the sides and at the bottom of the rut, but in very wet to saturated soils rutting can occur without compaction (Arnup 1998). Rutting not necessarily increase the bulk density because wet soil has a low air-filled porosity. Rutting can affect soil mixing, decrease the porosity, decrease the thickness of the root mat layer and may also cause damage to roots.

1.4.1 Tree roots

A typical forest soil consists of a large amount of roots that are buried in several relatively thin layers. According to Wästerlund (1989), most of the roots are found within the surface of 1m of the soils, with the majority of fine, non-woody roots in the upper 10 cm of soil. There can be as many as 300-500 roots per square meter. Root distribution and growth patterns seem to be exceedingly diverse both in the same species (e.g. under different environmental conditions) and between different species, with some exhibiting changing architecture as they develop.

Roots in forest soils significantly reinforce soil as long as they do not break. Until now, soil-vehicle mechanics seldom take this effect into account, which depends on the mechanical properties of the soil itself, the mechanical properties of the root material, soil-root interface properties, the morphology of the root system and loading characteristics (Cofie 2001). The benefit from roots is expected to be higher in weak soils than in strong soils.

2 The WES-method

In this method, vehicles are tested in a range of terrains and at the same time the terrain is identified by field observations and simplified measurements. Then, the parameter values of the empirical model are adapted to correlate to the field tests. From this, the model can be used to develop a scale for evaluating terrain trafficability and vehicle mobility. This approach was pioneered by the US Army Waterways Experiment Station (WES) during the Second World War. Recently, this approach has been extended, for instance, to empirically correlate certain dimensionless performance parameters of tires with mobility numbers (numerics) based on the cone index (Wong 2010).

WES Vehicle Cone Index Model (VCI) is an empirical model to predict vehicle performance for fine coarse-grained inorganic soils. It includes determination of minimum soil strength requirements in terms of vehicle cone index, maximum towing force, and towed motion resistance while a vehicle is traveling in a straight line in constant velocity motion on unobstructed level and sloping soil surface. All of the performance parameters are related to Rating Cone Index (RCI) for fine-grained soils and Cone Index (CI) for coarse-grained soils. WES Mobility Numeric Model is also essentially empirical and, at this time, is applicable to pneumatic-tired vehicles. The mobility numeric model is based upon generalization of systematic single wheel tests on prepared homogeneous soils (Rula et al. 1971).

Important factors that affect the vehicles drawbar pull and the rolling resistance are the mechanical properties of the soil, tire size and inflation pressure, dynamic wheel load, and wheel slip. Many researchers have investigated these factors and proposed traction prediction equations for different field and operating conditions. Many authors have developed adapted models for mobility prediction based on the WES-method.

The WES-method has not been developed for the purpose to predict the evaluation of soil disturbance or other environmental effects of the terrain tractors, but it can be extended to evaluate wheel sinkage, rut formation and soil compaction (Saarilahti 2002).

2.1 Wheel numeric

In the WES-method, vehicle parameters are defined as dimensionless quantities called wheel numeric, calculated from wheel dimensions and slip based on simple models and theories. Different wheel numerics have been developed by different researchers, based on observations on the wheel-soil interaction. Wismer and Luth(1973) developed a model that does not consider tire deflection and section height, but it is one of the rut depth models recommended by Saarilahti for the simple forwarder model:

$$\mathrm{C_N} = \frac{\mathrm{CI \cdot b \cdot d}}{\mathrm{W}} \quad (5)$$

Where, C_N is wheel numeric; d is tire diameter (m); W is wheel load and (kN) and CI is cone index.

Turnage developed the following model based on the tests performed on sandy and clay soils (Saarilahti 2002):

$$N_{CI} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \cdot \frac{1}{\left(1+\frac{b \cdot d}{2}\right)} \quad (6)$$

Where N_{CI} is wheel numeric; δ is tire deflection(m) and h is tire section height (m).

2.2 Tire deflection

Tire deflection depends on tire carcass stiffness, structure (cross ply or radial), ply rating/number of structure layers and tire inflation pressure. Of which, tire inflation pressure is the dominant determining factor for forestry tires. The best estimate for forwarder tire deflection becomes;

$$\delta = 0.008 + 0.001 \cdot \left(0.365 + \frac{170}{P_i}\right) \cdot W \quad (7)$$

Where p_i is inflation pressure (kPa).

2.3 Single-pass rut depth models

Saarilahti with his simple forwarder model has suggested several first wheel pass/ vehicle pass models suitable for forest machines, such as:

$$Z_{rut} = 0.003 + \frac{0.0380}{N_{CC}} \quad (8)$$

$$Z_{rut} = \frac{0.328}{N_{CI}} \quad (9)$$

$$Z_{rut} = 0.005 \cdot \frac{1.212}{C_N} \quad (10)$$

Eq. 8, 9, and 10 were developed by Anttila (1998)for first cycle pass. The term cycle pass basically refers to different load cases in each pass (e.g. the vehicle enters the terrain empty and leaves loaded) and treats the rut depth values after the entire vehicle has passed a certain point.Therefore the constant used in Anttila's models are quite specific to the vehicle used and actual load cases.

The model in Eq. 11 was introduced by Saarilahti, based on specially fitted forest tractors with tracks on tandem axles, even though the wheel numerics are calculated for a simple wheel. Therefore the model may give some underestimates for normal tractors on peatland.

$$Z_{rut} = \frac{0.142}{N_{CI}^{0.83}} \quad (11)$$

$$Z_{rut} = d \cdot \frac{0.224}{N_{CI}^{1.25}} \quad (12)$$

Maclaurin's (1990)rut depth model (Eq. 12) is based on the first wheel pass rut depth. To find first vehicle pass, a multi-pass rut depth model should be used (if the vehicle has 4 wheels on each side, the fourth wheel pass is equal to the vehicle pass).

Rantala (2001) compared three different methods to predict the rut formation and developed the following models:

$$Z_{rut} = \frac{0.989}{N_{CI}^{1.23}} \quad (13)$$

Gee-Glough (1985) developed the following sinkage model:

$$Z_{rut} = \frac{0.287}{N_{CI}} \cdot \frac{d}{\left(0.63+0.34 \cdot \frac{b}{d}\right)^2} \quad (14)$$

2.5 Multi-pass rut depth models

Scholander (1973) found a general equation for the settlement during load test:

$$S_n = S_1 \cdot n^{\frac{1}{a}} \quad (15)$$

Where S_n is settlement after n^{th} loading cycle; S_1 is settlement after first loading cycle, n is number of number of cycles.

After that Abebe et al. (1989) introduced a multi-pass sinkage model, which is in fact similar to Scholander's model, but the terms settlement and repeatedness have been replaced with sinkage and multi-pass.

$$S_n = S_1 \cdot n^{\frac{1}{a}} \quad (16)$$

He recommended multi-pass coefficients between 2 to 3 for loose soils. The coefficient a can be calculated from an empirical data matrix, as shown in the following equation (Saarilahti 2002):

$$a = \frac{\ln(z_j) - \ln(z_i)}{\ln(j) - \ln(i)} \quad (17)$$

where, i, j are ordinary numbers of passes.

3 Materials and methods

Field tests were carried out by The Forestry Research Institute of Sweden, Skogforsk, and the Swedish University of Agricultural Sciences, SLU, in September, 2011. The aim for the test was to study the how rutting and soil compactionwas affected by the number of passes by loaded and unloaded forwarders with different tire inflation pressures.

3.1 The site

The soil at the examined site was similar to some forest soils with respect to its content and elastic property. It consisted of three layers: the uppermost layer was peaty soil while the middle and the bottom were sand and clay, respectively, see Fig 1. The thickness of the peaty soil layer varied between 10 cm and 15 cm. The top layer consisted of non-homogeneous vegetation, especially grass. The site surface was level.

The soil moisture content was measured on the first and last days of testing. Soil moisture content indicates the amount of water present in soil. It is commonly expressed as the amount of water (in mm of water depth) present in a depth of 1m of soil. The moisture content differed between different tracks, but did not change quite substantially along the same track.

Figure 1: Soil distribution in the test terrain

The average value on the starting day was 52.7% and on the last day 51.9%

3.2 The forwarders

One of the two forwarders used in the test was a Valmet 860 forwarder equipped with Trelleborg 710/50x26.5 T428 163A8 forestry tires. The forwarder was driven at 3 km/h.

In the first phase of the experiment, the empty and loaded weights of the forwarder were measured by placing a scale under each wheel. Themachine weight of the forwarder was 19170 kg and the load used was 10500 kg (75% of the full load capacity). In order to determine how tire inflation pressure affects the rut depths, the Valmet 860 (unloaded and loaded) was tested with a low tire pressure (270 kPa), a medium tire pressure (450 kPa), and a high inflation pressure (600 kPa).

3.3 Physical experiments

All experiments were held on a large field which is divided into 16 m long and 3 m wide plots. These plots were split in 2 m distance in the driving direction.

First of all, the soil was investigated for its physical and mechanical properties such as moisture content and penetration resistance. Cone index was measured by a Eijkelkamp Penetrologger equipped with a 3.33 cm^2 cone.

Earth pressure was measured using three pressure sensors installed at 15cm intervals below the ground surface and connected to PCs that store the measured pressure time-histories (Fig. 2).

The rut depth was measured using a simple meter consisting of a set of vertical metal rods. The metal was placed across the wheel rut perpendicular to the direction of travel. After each vehicle passage, the cone index and rut depth were measured at 2 m intervals along 16 m in the driving direction.

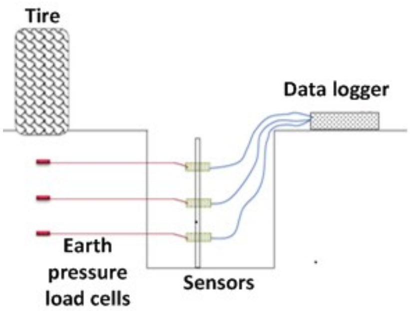

Figure 2: Setup for soil pressure measurements

4 Results

Cone penetration measurements were made before the first pass and after every second pass. At each measuring point, the penetration resistance was measured from 0 cm to 30 cm below the surface at 1cm intervals. The bearing capacity was as low as 300 kPa at a depth of 1 cm due to the presence of peaty soils. Anttila (1998) noticed that the penetration resistance measured at 15cm depth had the highest predictive power. The same fact was used to determine the depth at which cone index values to be used for analysis. Between a depth of about 5cm and a depth between 15 and 18 cm, the cone index value became quite constant, averaging approximately 1200 kPa. Fig. 3 shows soil penetration resistance after single and 10 passes of the forwarder with medium and high tire pressure.

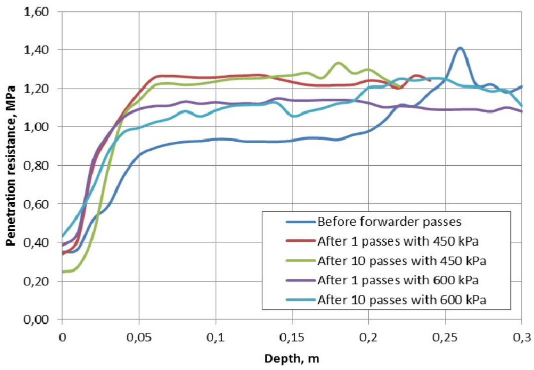

Figure 3: Soil penetration resistance of Valmet 860

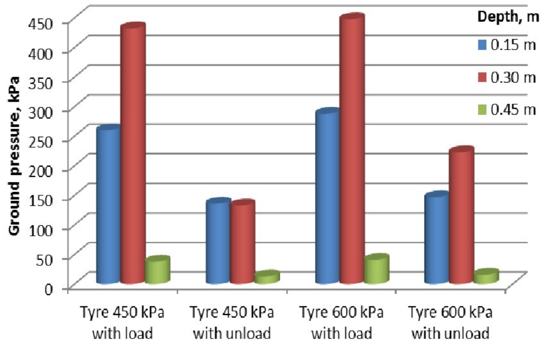

Figure 4: Ground pressure

Fig. 4 shows the Valmet 860 ground pressure measured in the field tests. The ground pressure values were compared with available ground pressure models, presented in the publication from Saarilahti (2002). Some of the models provide onlythe contact area, thus the mean contact pressure is calculated by dividing the wheel load by the contact area. Only the models in which all the parameters are known were used in the analysis. However, no models were distinguished in terms of soil type. The actual measured pressure values show a clear increase in the ground pressure with an increase in the contact pressure. Fig. 5 shows the comparison with the measured ground pressures for a loaded Valmet 860, with an inflation pressure of 450 kPa. The average wheel load from the rear measurements was used in the models. Many studies have shown that ground pressure distribution underneath a wheel is not even.

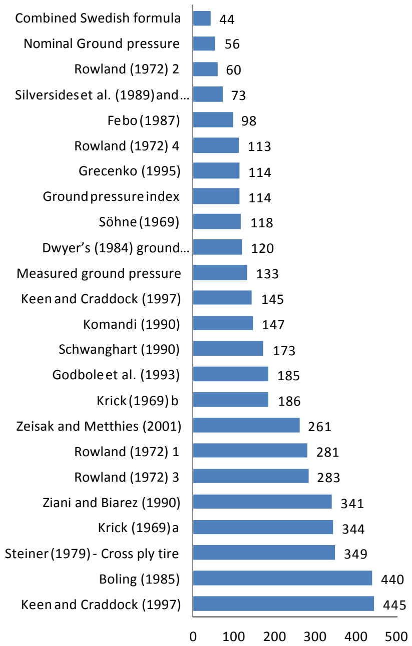

Figure 5: Ground pressure comparison with measured ground pressure for a loaded Valmet 860

The results postulate that there is no universally acceptable model available for predicting ground pressure values. Also some models require a set of model specific parameter values. For example, the mean maximum pressure models developed by Rowland (1972) require the entire vehicle weight which is in reality not evenly distributed among all the axles and wheels. An unloaded forwarder has a higher load on the front wheels, but loading the forwarder shifts the center of gravity closer to the rear wheels. None of the models directly depend on the cone index. A few consider tire sinkage, which was estimated using cone index (with wheel numeric N_{CI} and Maclaurin's model), e.g. by Söhne (1969) andKeen and

Craddock (1997). Many models are originally based on rigid plate theories, which are applicable for foundations. Also all the models assumes a static position of the wheel, i.e. they neglect the effect from dynamic loadings.

The measured rut depth results did not differ significantly between the first and the fifth forwarder passage, but a difference was observed when the number of passages raised to 10. Fig.6shows the measured rut depth values on different tracks after each passage. The rut depth values were obtained only for 450 and 600 kPa inflation pressure. It can be observed that ruts get deeper with an increased number of passages, an increased wheel load, and with an increase in the inflation pressure. To observe the impact from each parameter better, one parameter needs be changed while leaving the others constant, as for example shown in figure 6.

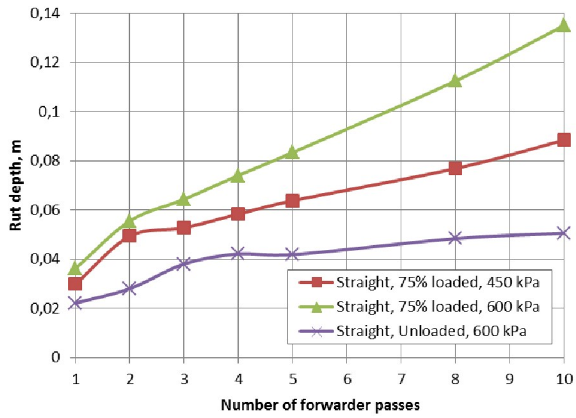

Figure 6: Rut depth values for a Valmet 860

The rut depth curves of a Valmet 860 on a straight track with medium and high tire inflation pressure are shown in Fig 7.

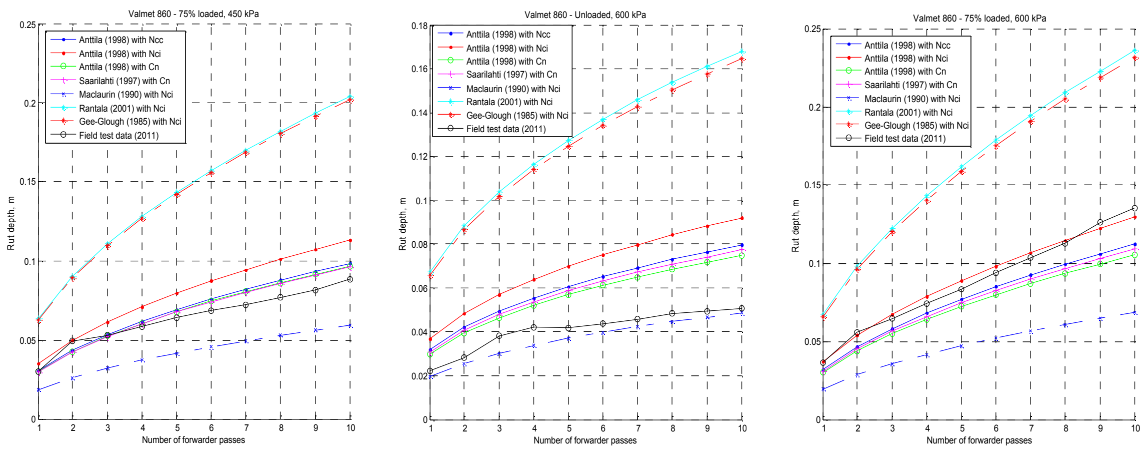

Figure 7: Comparison of multi-pass rut depth values from different models and field test data, with multi pass coefficient a=1.97 (top), 2.51 (mid), 1.83 (bottom)

The multi-pass rut depth values estimated from first vehicle pass formulas by Anttila's (1998), Saarilahti's (1997), Maclaurin's (1990), Rantala (2001), and Gee-Glough's (1985) are also shown. The vehicle multi-passes were estimated with the Abebe formula. The multi-pass coefficient was calculated and manually fitted from field test data by Eq.(17). For all calculations, an average cone index value of 1200 kPa was used.

5 Multi-body simulation of forest machine

A multi-body simulation (MBS) model of Komatsu Valmet 860.3 forwarder was developed in MD Adams(an advanced MBS software) at KTH, Sweden. The intension of modellingwas to study vibrations the driver is exposed while driving, whereby to explore new design solutions to minimize vibration levels. The original model simulated a test track of hard ground; thereforethe model was improved to work on soft soil.

The ADAMS soft-soil road model was chosen to develop the tire-soft soil interaction. Since version 2010, Adams/Tire offers a new tire model that predicts the interaction forces between a tire and a soft soil ground. The tire model uses knowledge about terra-mechanical tire-soil interaction as published by Bekker, Wong, Janosi, Ishigami and Schmid (ADAMS 2012). The application range covers the basic driving manoeuvres with 'one-point' of contact tire-road methods in which no excessive camber occurs.

Both flat and steep terrains were simulated in the model. The purpose of modellinga steep terrain was to ensure whether Adams soft soil model can be successfully adapted to large scale simulations.Tire properties were according to Trelleborg 710/45-26.5 T428 163A8 forestry tire. Road model requests soil parameters according to Bekker's tire model and additionally some elastic-plastic and viscoelastic properties.The model performed well ran (fig. 8) on both terrain types. Soil properties were according to Rubican (Wong 2008) soil, which has similarities to Nordic forestry soil.

Figure 8: Simulation of Valmet 860.3 on soft soil steep terrain

5.1 Comparison of simulations with the WES-method

For comparison, results from several simulations had to be compared, thus, use of Valmet 860.3 model was not feasible. Therefore verification was achieved through simulating a single wheel. A time dependant incremental vertical load was applied to the centre of a separately modelled tire ranging from 0 - 30 kN.

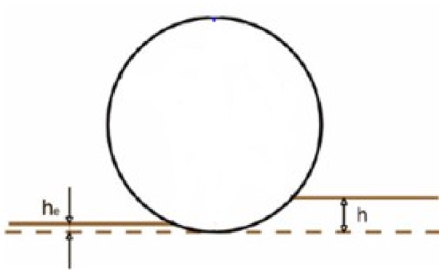

Figure 9: Plastic deformation of soil (h-h_e)

Adams model considers rut depth as plastic soil deformation. Plastic deformation is the difference between sinkage (h) (from Bekker's tire model) and exit (h_e) penetration, see Fig. 9.

The single-wheel model was tested with several soil types given by Wong (2008). For WES-method, two formulas were used i.e. (Maclaurin 1990)and Maclaurin's formula with constant values fitted to match test data. Those constants were found using non-linear regression analysis, i.e. finding the best fitting curve for measured rut depth values (y axis) and the corresponding parameter values (x axis) for each rut depth. Note that modified Maclaurin's formula gives first vehicle pass rut depth. Figure 10shows a comparison of rut depth values at 400 kPa inflation pressure.Rubican (Wong) soil had somewhat closer values with rut test results and Maclaurin's method. Change of inflation pressure had an effect on sinkage but not the curve shapes, yet Rubican was the closest for all.

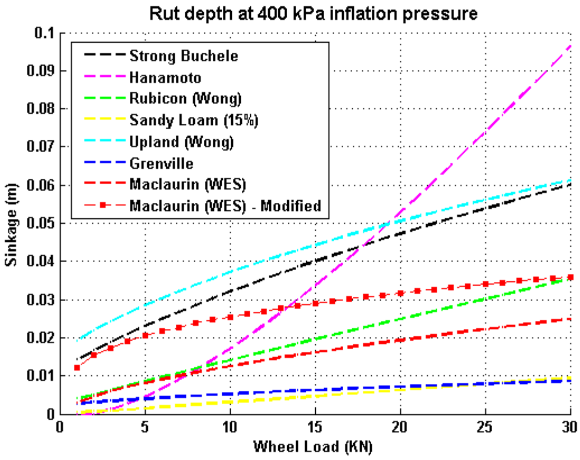

Figure 10: Comparison of Adams results with WES

6 Discussion

The Abebe (1989) model can be used to make better estimates of multi-pass rut depths. Estimated multi-pass coefficients are within the range Abebe proposed for soft soil (i.e. 2-3). Maclaurin (1990) provided the best estimation of rut depth (fig 7.b) for an unloaded forwarder. In that estimation, the multi-pass coefficient values used to find the fourth wheel pass was within the range of 2-3, close to the range (2-3) presented in Abebes studies. Fig. 7 (top and mid) shows the multi-pass rut depth values of an 75% loaded forwarder with 450 kPa and 600 kPa tire inflation pressure. In that case, the multi-pass coefficient estimated from test data by Eq. (17) was lower than the coefficient from Abebe (1989) and close to Anttila(1997).

In Forestry tires, lug heights are larger (2-3 cm), so their influence on the rut depth may be greater, resulting in a large variation (> 1 cm).

A more complete analysis would have been made if more data of some parameters had been available. For example, cone index was averaged because values were not available for all the tracks. The soil type was the same, but a minor variation (about 50 kPa) was noticed.

For ground pressure, most of the models gave somewhat unrealistic values, especially the ones that underestimated the actual value. The measured ground pressure data may not represent the actual condition as load cells were buried 15 cm below the ground. To have more detailed results, they would have been installed closer to the tire-soil interface, but then the load cells would have been more susceptible to damage. For every model, the applicable ground condition (including soil content and moisture condition) needs to be provided.

Contribution from roots to the soil bearing capacity is a challenging problem due to the complex nature of the root layer. Contribution from individual root elements can be effectively used in soil longitudinal shear analysis such as shear damage to the terrain by vehicles and landslide analysis. For bearing capacity, the behavior of roots is unpredictable because they form an un-isotropic mesh type layer in the soil. Analytical models can be applied, but the accuracy may be debatable. Results show that the number of roots underneath the tire, the length of the affected area of roots, and the soil types have great influence on the bearing capacity. Root breaking is associated with tangential friction and root slippage, where experimental data are scarce, so a successful prediction of root failure and an analysis of its consequences are difficult to perform.

7 Conclusion

The test data did not match very well with existing models for reasons such as; the developed models are vehicle specific and soil condition specific. However the data did not deviate too much from the existing WES models. Multi-pass coefficients values were within the range that Abebe recommended for unloaded forwarders on soft soil. Existing models can be made consistent with test data by changing constants, however for better accuracy; more test data are needed.

The models with modified parameters can better estimate rut depth values associated with similar types of machines and the soil. From the original models, estimated values using Maclaurin's and Anttila's method have close similarity to first wheel pass rut depth data. Abebe's model can be used to estimate multi-pass rut depths.

Different contact pressure models gave different pressure levels indicating that a large number of test data are needed to conclude which model that is most useful for forestry applications.

The proposed models show that a good estimation of bearing capacity is possible with analytical models. A proper selection of parameter values has a great influence on the results. The models need to be verified with field tests, laboratory tests, and simulations. Root failure mechanism under wheel load should be further studied.

Adams soft soil road model can be used to estimate mobility and terrain damage to a satisfactory level, whereas its suitability for ride comfort analysis needs to be verified using experimental data.

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Further work

The reinforcement effects from roots are currently under investigation. It is still an open issue how these effects should be most efficiently modeled to be useful in fine-grain multi-body dynamic simulations and how the model should be validated.

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