Evaluation of Forwarder Multipassing on Soil Compaction

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Abstract:
In Croatia forwarders are the most common machines for wood extraction from shelterwood fellings. Due to their large mass and large load mass as well as due to increased soil moisture in winter–spring period, forwarders can cause great soil disturbance. The aim of this paper is to investigate the influence of forwarder multipassing on soil compaction in forwarder ruts, after preparatory felling in a penduculate oak (Quercus robur L.) lowland stand.
The research was conducted in favorable soil conditions that can be classified as (very)strong soil by EcoWood classification.
The evaluation of soil strength is based on three soil strength parameters: cone index measured by cone penetrometer, and shear strength measured by shear vane at two depths (on the surface and at 15 cm depth). The amount of transported wood (forwarder mass) was measured with portable scales. The highest coefficient of variation, as indicator of dispersion, is shown by measuring shear strength on soil surface, and then by measuring cone index, while the lowest coefficient of variation is shown by measuring shear strength at the depth of 15 cm.
Research results show (no) statistically significant differences among forwarder multipassing on soil compaction.

Keywords: forwarder, forwarder multipassing, soil compaction, soil strength, coefficient of variation

1 Introduction

Forest vehicles, due to their continuous contact with the soil and movement around the stand, run the risk of causing damage to forests and forest soil. However, soil is most affected by this action, and only some works or parts of these works also affect the vegetation. Differentiation should be made between two expressions:

⇒ Soil treading, defined as part of surface on which vehicles move compared to the total stand surface,

⇒ Soil compaction, determined as its volume deformation.

Preparatory works and other organizational measures can have a serious impact on soil treading, while soil compaction is decisively affected by vehicles and soil condition.

Horvat (1995) investigated natural recovery, i.e. the degree of soil compaction as one of many indicators of recovery after multipassing of a heavy forwarder in1984 and made comparison with the same measurement made after 10 years. Based on the performed measurements and analyses, he concluded that after 10 years of natural recovery, free of vehicles, the tested soil fully recovered and showed satisfactory compaction level.

Along with the indisputable impact of vehicles on soil compaction, and on plant increment, the conclusions of Wasterlund (1989) should also be outlined. He considers that damages can be reduced to approximately 5%, as compared to the established 10 to 15%.

In Croatian lowland forests, characterized by excessive soil moisture, as stated by Anić (2001) and Poršinsky (2005), special forest vehicles, forwarders, are used for wood extraction, mainly intended for timber extraction in regeneration felling i.e. in winter period (Oct. 1 to March 30). Due to considerable total mass of loaded forwarders (medium forwarder up to 30 tons) and frequently unfavorable soil strength in winter period, damage can be caused to forest soil in the form of soil deformation – wheel ruts and soil compaction.

2 Scope of research

The effect of forest vehicles depends on terrain (soil) accessibility and vehicle mobility. The accessibility of an area consists of several terrain and soil factors. Terrain is frequently described by terrain slope and occurrence of obstacles. Soil factors are used to describe soil reaction under the loaded wheel. Two data are necessary for describing the soil reaction: deformation and compaction of forest soil affected by vertical force and reaction of soil particles affected by horizontal force (Saarilahti 2002). There is no a general physical approach to soil accessibility unless it contains both soil and vehicle indicators (Baker 1960). According to Horvat (1993), the commonly used expressions such as vehicle maneuverability, vehicle mobility index and similar, assess the capability of vehicles to pass on a certain terrain regardless of consequences, and hence they do not describe well enough the vehicle–soil environmental component.

By the development of the empirical research method of the complex wheel–soil or vehicle-soil system, in reference literature known as WES method (*Waterways Experimentation Station, US Army Engineering Corps*), wheel numeric is used for correlating the characteristics of vehicles and soil deformation with soil strength.

$$N_k = \frac{CI \cdot A}{G_k} \tag{1}$$

Wheel numericis a non-dimensional parameter (factor) that describes the interaction of the loaded wheel and soil. It is determined by the ratio of contact pressure between wheel and soil and the soil strength estimated by measuring the soil strength by cone penetrometer. In practice, standardized measurement value of cone penetration resistance is used (ASAE EP524 1999) at the depth of 15 cm, called cone index (*CI*). Due to non-homogeneity of soil structure, Ronai (1983), Horvat (1993, 1994), Poršinsky (2005), Pandur et al.(2010), Horvat et al.(2011), Zorić et al.(2011) notice high data dispersion between repeated measurements of penetration characteristics.

The suitability of empirical method is also confirmed by terrain classification for performing forest works made by EcoWood project (Owende et al. 2002; Ward and Owende 2003) shown in Table 1. This terrain classification is based on mechanical soil characteristics (*CI*, *E*, ²) and the parameter of vehicles is determined by its allowed ground pressure (*NGP*), expressed as nominal ground pressure (Mellgren 1980). Horvat et al. (2011), due to the lack of *NGP* data, supplemented the data used for EcoWood terrain classification with the $CI{*}NGP^{-1}$ ratio.

Table 1: EcoWood soil classification

Soil strength		Soil strength parameters			Allowed vehicle nominal ground pressure, NGP [kPa]	Ratio $\frac{CI}{NGP}$
Classes	Soil description	Cone Index, CI [kPa]	Module E [MPa]	Shear strength, ² [kPa]		
1	Strong soil	> 500	> 60	> 60	> 80	> 6.25
2	Average soil	300 – 500	20 – 60	20 – 60	60 – 80	5 – 6.25
3	Soft soil	< 300	< 20	< 20	40 – 60	< 5
4	Very soft soil	<< 300	<< 20	<< 20	< 40	<< 5

The empirical method for determining the soil strength by penetrometer is supplemented with the data of the soil shear strength measured by a vane tester. The vane tester is an instrument consisting of a measuring vane attached to a bar equipped with a torque moment meter, the device used for measuring the moment required for the vane to turn at the moment of overcoming the shear strength along the roller external circumference around the vanes (Nonveiller 1979).

The measuring vanes are two metal sheets of height (*H*) and breadth (*B*) crossly attached to the metal rod. Najdanović (1967) recommends the use of measuring vanes with the following ratio of sheet dimensions:

$$H = 2 \cdot B \tag{2}$$

Endo (1980), Gray and Sotir (1996) outline that soil roots affect considerably the soil shear strength. Mickovski et al. (2009) outline that the soil shear strength depends significantly on root diameter. As their conclusions were made based on results obtained in controlled conditions, it can be assumed that the roots of trees, brushwood and shrubbery would affect significantly the measurement of the soil shear strength in a natural stand.

The objectives of this paper were to establish the actual distribution of weights (mass) by forwarder wheels (axles), determine the pressure under the wheels using semi-empirical expressions for calculating the pressure under the wheels, determine the change of mechanical characteristics of the soil caused by increased load by measuring the cone index (*CI*) and shear strength, and based on the calculated wheel numeric, estimate the environmental viability of forwarders.

3 Materials and methods

The research was carried out in the area of Vinkovci Forest Administration, Otok Forest Office, M.U. „Slavir“ in the compartment 143c. This is low lying land, a little elevated in the south-east part. Cone index and soil shear strength in the compartment 143c were measured at 19 measurement sites (Fig. 1). The measurement sites were divided into 6 measurement groups with respect to the number of forwarder passes. The measurement groups ranged from one measuring site (group A) to maximum four measurement sites (group C, D and E). Table 2 shows the distribution of measurement sites by groups.

Table 2: Distribution of measurement sites

Group	Number of forwarder passes	Measurement site
A	13	1
B	10	2, 7, 15
C	8	3, 8, 10, 17
D	6	4, 9, 16, 19
E	5	5, 12, 13, 18
F	4	6, 11, 14

The compartment soil is wetland gley (eugley)-hipogley. Eugley is mostly clayey soil, continuously wet, on which plants lack oxygen and hence in natural conditions, on such soils, only plants that can endure the lack of oxygen can grow (e.g. European ash, pedunculate oak). Fig. 2 shows the granulometric composition of the soil in the investigated compartment.

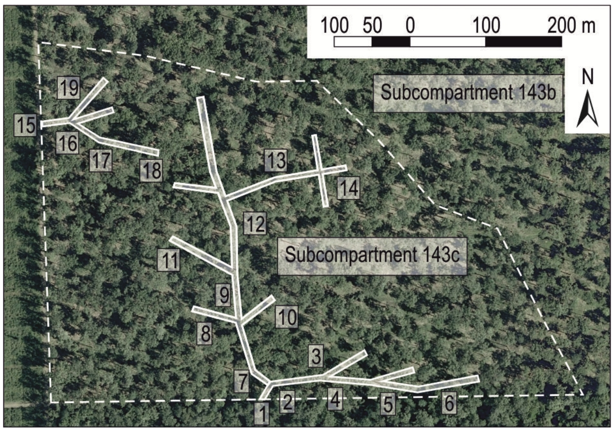

Figure 1: Position of measurement sites

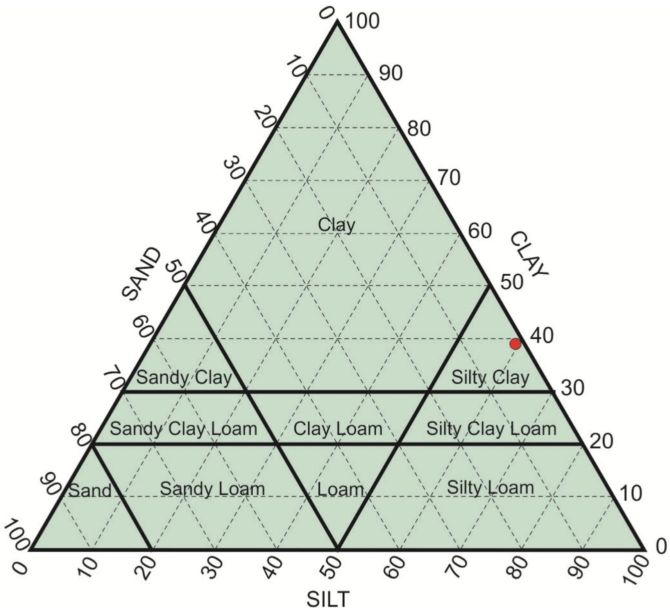

Figure 2: Granulometric composition of soil

When gathering data on the soil condition, use was made of the digital penetrometer Eijkelkamp Penetrologger (Fig. 3) with the cone basis crosscut of 2 cm^2 and point angle of 30° in accordance with ASAE S313.3 (1999) Standard. The soil shear resistance (shear strength) was measured by the *Eijkelkamp – Field inspection Vane tester*. The dimensions of tester vanes were 20 mm x 40 mm, and the measuring area of this instrument ranged between 0 and 130 kPa, with the reading precision of the measuring result of 2 kPa. The measuring result of this instrument is related to the soil shear resistance at its breakage.

Figure 3: Penetration

Figure 4: Portable scales inside metal case

Portable scales were used for measuring the axle loads, and their calibration was described by Bosner (2008). The scales were inserted into a metal platform, on which the forwarder was positioned so as to be protected from damaging and placed on the scales as precisely as possible to minimize the measuring error, as shown in Fig. 4.

The object of this research is a Valmet 840.2. forwarder (Fig. 5). From the standpoint of economical use, the demand of the Croatian forestry is a forwarder with the carrying capacity up to 14 t and hydraulic crane with the lifting capacity of 100 kNm required for loading and extraction of large logs from main felling sites (Horvat and Poršinsky 2000). Through the history of forwarder research, different classifications have been developed based on which forwarders have been divided into groups according to net mass, carrying capacity and gross mass (Poršinsky 1997). According to the latest forwarder classification given by Brunberg (2004), the forwarder investigated in this paper is classified in the group of medium forwarders.

One of the significant components of this research is the determination of characteristics (dimensions) of forwarder tires, shown in Table 3.

Table 3: Review of used tires

Tire position	Tire model	Radius r [m]	Width b [m]	Deflection δ [m]	Contact area A = r b [m^2]
		Forwarder			
Front	NOKIAN TRS L - 2 600/65 - 34	0.78	0.601	0.05	0.469
Bogie	NOKIAN TRS LS - 2 600/55 - 26.5	0.66	0.6	0.02	0.396

Figure 5: Researched forwarder Valmet 840.2

4 Research results

At each site, 5 measurements were made by penetrometer and 5 measurements by vane tester at the depth of 0 cm and 15 cm. The measurement was made vertically on wheel rut, and the measurement scheme of one measurement site with the results expressed for the measurement site 1 is shown in figure 6.

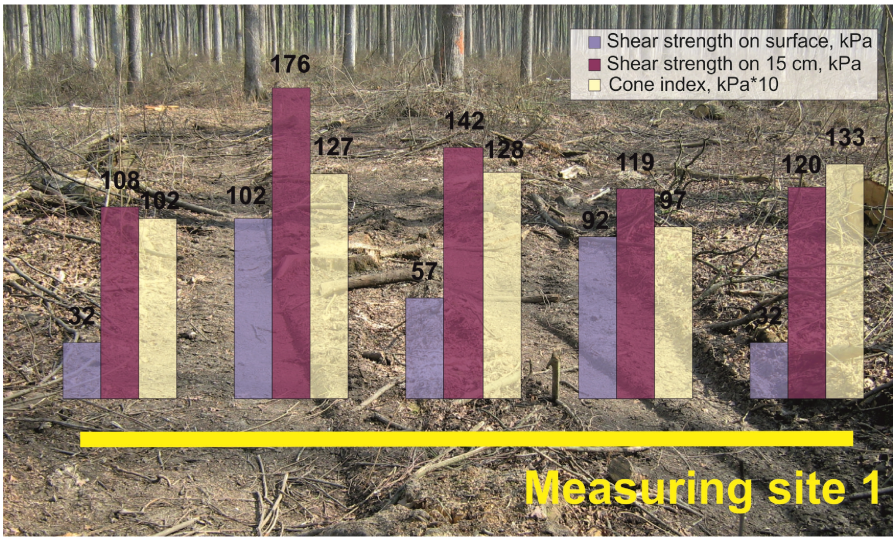

Figure 6: Principle of measuring and results for measurement site 1

Penetration curves are the results of measurement of penetrometer characteristics – 5 per each measurement site, and Fig. 7 shows the results for measurement site 1. In accordance with the standard, values of cone index at the depth of 15 cm are read from the diagram in Fig. 7. The cone index for the stand in the researched compartment was 980 kPa – median of all measurements. According to EcoWood terrain classification, the soil of the stand can be classified as (very) strong. It means that the maximum allowed value of the nominal pressure is higher than 80 kPa.

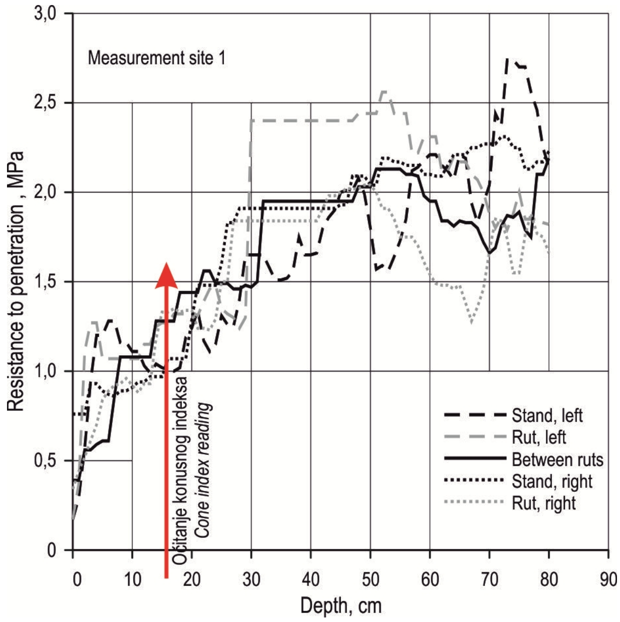

Figure 7: Penetration curve for measurement site 1

After felling and processing, technical roundwood was extracted from the compartment by forwarder, 24 rounds in total. The total load volume measured by a traditional forestry method was 278.15 m^3 of roundwood. The total mass of 259,000 kg of transported wood was determined by weighing the forwarder by the described method. Table 4 presents the wheel numeric calculated on the basis of the expression for the wheel numeric presented in the Chapter "Materials and methods" and the measured distribution of forwarder masses and the measured cone index of the stand soil. Only one value was calculated for the front wheel, because the mass on the front axle of the loaded and empty forwarder differed only slightly. Table 4 clearly shows that for the tested forwarder, its unloaded bogie system has the highest wheel numeric of 21.13 and the best mobility, while the loaded bogie system with wheel numeric of 8.93 has the worst mobility.

Table 4: Values of cone index, nominal ground pressure and wheel numeric for the stand

	Front wheel of forwarder loaded/unloaded	**Bogie wheel of forwarder, unloaded**	**Bogie wheel of forwarder, loaded**
CI – Cone index, kPa	980	980	980
τ – Shear strength on surface, kPa	30	30	30
τ – Shear strength on 15 cm depth, kPa	112	112	112
G – Wheel load, kN	44.7	18.37	43.47
A – Contact area, m^2	0.469	0.396	0.396
NGP – Nominal ground pressure, kPa	95.31	46.39	109.77
Wheel numeric N_k (Mellgren)	10.28	21.13	8.93

It can be seen in Table 4 that the front wheels and the wheel of the bogie axle of the loaded forwarder have the nominal ground pressure higher than 80 kPa, and to be specific the front wheels approximately by 20% (95.31 kPa) higher and the wheel of the bogie axle almost 40% higher (109.77 kPa). Based on EcoWood terrain classification, it can be said that on very strong soil of the stand (*CI* = 980 kPa, $^{2}{}_{\text{on surface}}$

= 30 kPa, $^{2}{}_{\text{on 15 cm depth}}$ = 112 kPa), the front wheels can be expected to move with almost no negative effects, while this cannot be said with certainty for the wheels of the bogie axle of the loaded forwarder. If wheel numeric is calculated, a numeric parameter is obtained that quantitatively describes better the criteria of mobility. So according to the calculated wheel numerics (10.28 and 8.93) it can be concluded with certainty that the effects of moving of front wheels of the loaded and empty forwarder as well as the wheel of the bogie axle of the loaded forwarder will be within acceptable limits. Bogie wheels of the empty forwarder with the nominal pressure of 46.39 kPa and wheel numeric of 21.13 will not cause damage to the soil of the stand.

Fig. 8 shows the values of the median of cone index (*CI*) for the stand, central part between wheel ruts and wheel ruts by measurement groups.

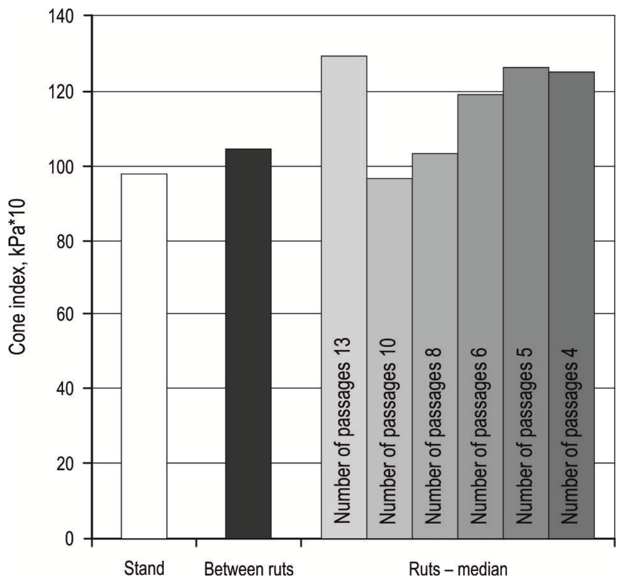

Figure 8: Average values of cone indexes depending on number of passes

The number of forwarder passes is lowered from group 1 to group 6. Fig. 8 shows that, regardless of the number of forwarder passes, there is no significant deformation of forest soil, i.e. soil compaction. This fact is contrary to expectations, because the cone index of wheel ruts and stand should differ considerably and the difference should increase with respect to the number of forwarder passes.

Fig. 9 shows the values of cone index and shear strength measured in the wheel rut on the surface and at the depth of 15 cm depending on the number of forwarder passes. Fig. 9 clearly shows that the trend line of the cone index deviates from the expected, i.e. that the cone index does not increase with the number of passes, while the trend line of the shear strength has the expected form, i.e. the shear strength of the soil increases with the number of forwarder passes.

The fact should be emphasized here that due to non-homogeneity of forest soil, its many layers and root interlacing of forest plants, shrubs and trees, the penetration curves for the stand, and consequently also the cone indexes and values of measurements made by vane tester show high dispersion. This statement is also confirmed by coefficients of variation calculated for each measured parameter of the stand (Table 5).

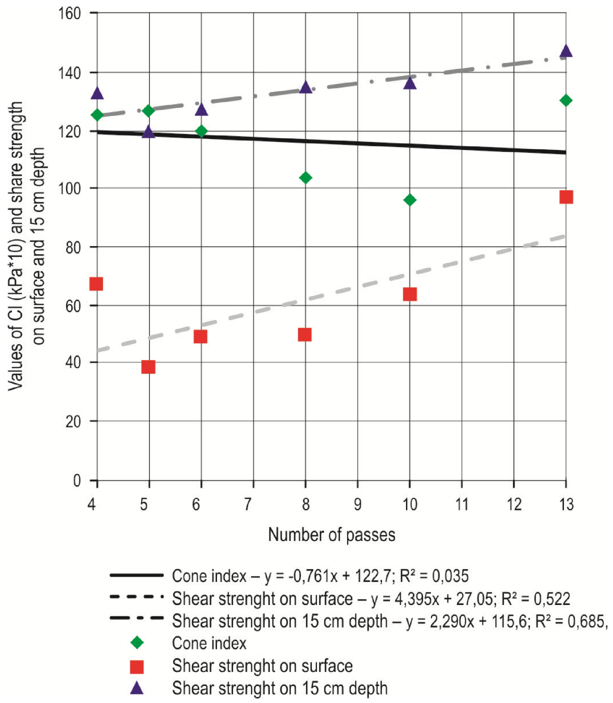

Figure 9: Relation between cone index, shear strength on surface, shear strength on 15 cm depth and number of passes

Table 5: Coefficient of variation of measured parameters

	Shear strength on surface	Shear strength on 15 cm depth	CI
Coefficient of variation	0,58	0,23	0,27

Fig. 10, 11 and 12 present graphs showing the relationship between the measured soil parameters. Fig. 10 shows the relationship between the cone index and soil shear strength measured on the surface. As it can be seen in Fig. 10 and from the related equation and correlation index, the connection between the cone index and shear strength on the surface is very poor.

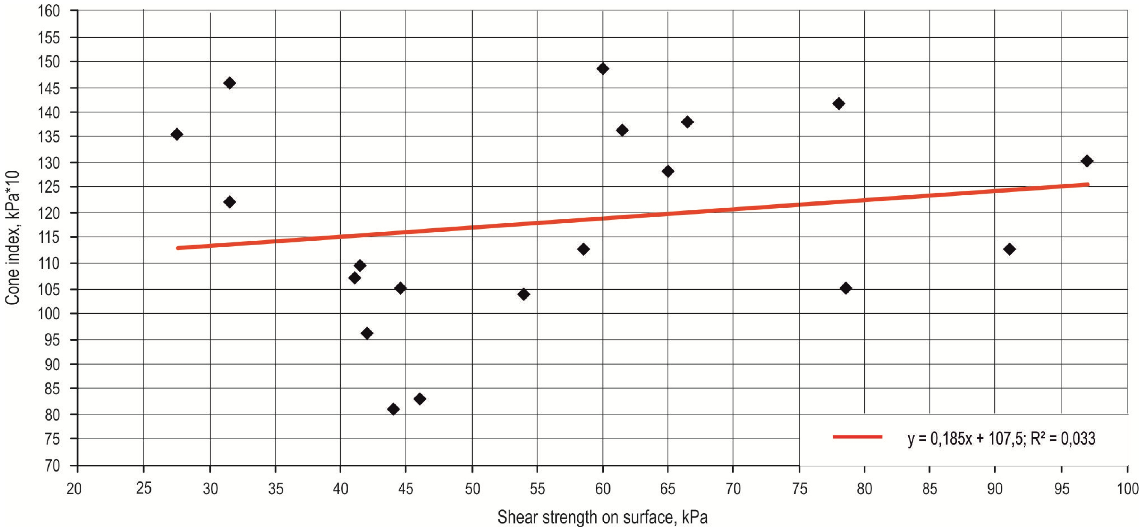

Figure 10: Relationship between cone index and shear strength on the surface

Fig. 11 shows the cone index and soil shear strength measured at the depth of 15 cm. As it can be seen in Fig. 11, there is no connection between the linear equation that describes the processed data and correlation index, cone index and soil shear strength.

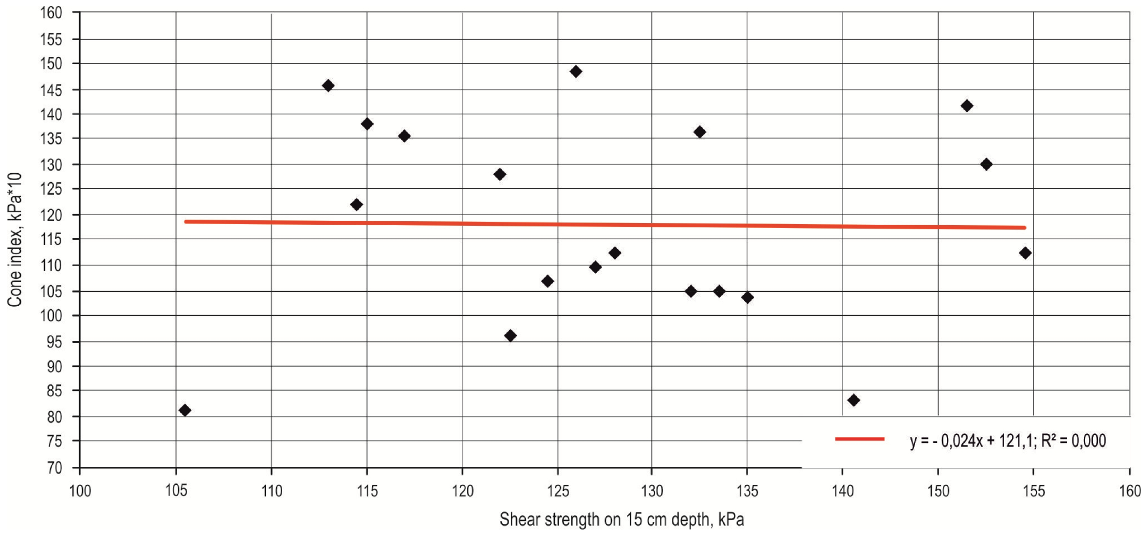

Figure 11: Relationship between cone index and shear strength at 15 cm depth

Fig. 12 shows the relatioship between soil shear strength on the surface and at the depth of 15 cm. It can be clearly seen that the analyzed data have a partly satisfying connection, which is also confirmed by the correlation index R^2=0.504.

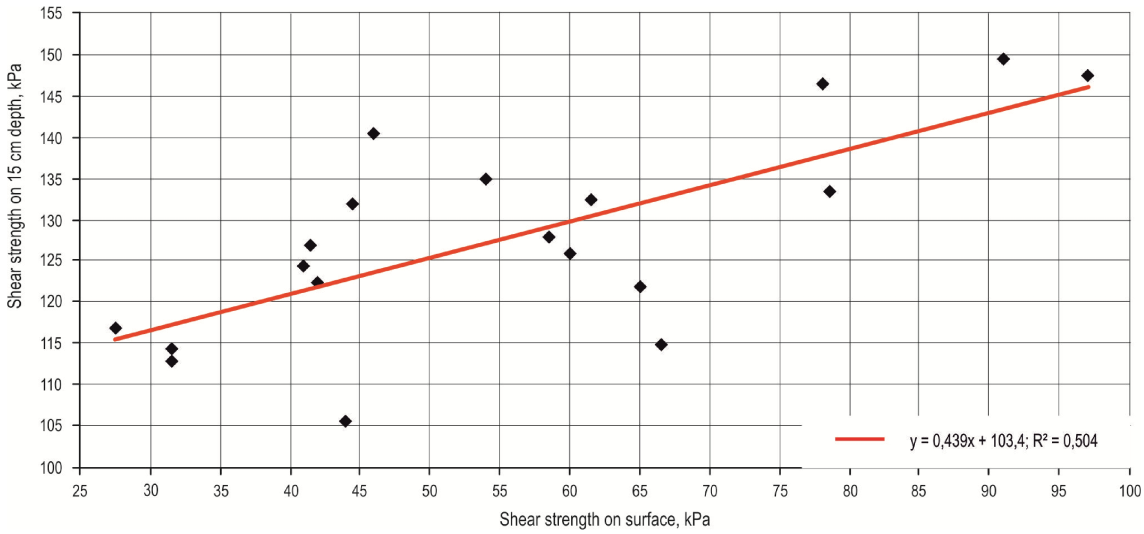

Figure 12: Relationship between surface and shear strength at 15 cm depth

In this way, too, the expectation according to Ecowood classification has been confirmed, and namely that forwarder moving on such strong soil will be within acceptable limits, as already concluded on the basis of nominal ground pressures and the pertaining wheel numerics.

Figure 14: Illustration of rut depth

5 Conclusion

It has been established that forwarder moving on strong soil does not cause significant soil compaction. In this way, the Ecowood classification has been confirmed for the strong soil which have cone index measured at the depth of 15 cm *CI*>500 kPa (980 kPa measured on average). According to the above classification, the shear strength for strong soils is ^{2}>60 kPa, and during the research, an average of 30 kPa was measured on the surface and 112 kPa at the depth of 15 cm. According to Ecowood classification for strong soils *NGP*>80 kPa, and the maximum established NGP of 109.77 kPa was recorded for the loaded bogie wheels, as well as the lowest wheel numeric N_k=8.93.

The fact has been confirmed that the data of soil characteristics measured by penetrometer and vane tester for such strong soil show high dispersion, which reduces their usability. The lowest dispersion was established with measurements of shear strength at the depth of 15 cm. Therefore, efforts should be focused on the development of a measurement method more suitable for the forest soil.

Influence of number of passes is more evident and more logical at measuring with share vane than with penetrometer. No satisfactory correlation has been established between the results of measurement of cone index and shear strength. The correlation was partly satisfactory only in the comparison of measurements of shear strength on the surface and at the depth of 15 cm.

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