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The relationship between precompression stress and rut depth of different soil types in Estonia

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Abstract. In agriculture as well for other purposes off-road vehicles have to move cross-country. Precompression stress is used to describe the load bearing capacity of different soils. The aim of the study is to investigate the relationship between precompression stress and rut depth for different Estonian soil types after 1 and 10 passes of a vehicle. Traffic experiments were conducted at eight experiment sites throughout Estonia using a 7 t truck and a 23 t wheeled vehicle. The experiment sites were selected based on the Estonian soil map. Rut depth was measured after the first pass and ten passes. Undisturbed soil samples were collected from topsoil and from subsoil right next to the track. Soil samples were compressed in an oedometer at stresses of 25, 50, 100, 200, 400 and 600 kPa. The Casagrande procedure was used to determine the precompression stresses. In topsoil, if the moisture content of a soil is high, then the differences in the precompression stress values of the various soil types disappears while in the subsoil layer the precompression stress is more dependent on the soil properties. The precompression stress cannot by itself be used as a threshold value to determine small and large sinkage. The choice of fitting methods for composing of stress compaction curve is critical and led to the preference of the logistic curve. The values of logistic functions at the points of their maximal curvature and calculation based on the area on stress-compaction graph can be used for prediction of rut depths.

Key words: soil bearing capacity, sinkage, soil compaction, logistic curve.

INTRODUCTION

In agriculture as well for other purposes off-road vehicles with different weights and contact pressure have to move cross-country. In many cases repeated passages over the same track is necessary. It is well known fact that the movement of vehicles over the landscape harms the soil environment by compacting it (Alakukku et al., 2003). Compaction of soils is induced by the stress that occurs from the contact between the vehicle and the soil. To stay mobile vehicles cannot cause deep sinkage and ruts. The compaction of agricultural soils can have an especially negative effect on the yield and growth of cereal grains. In Estonia the overall impact of soil compaction by vehicles was investigated by Kuht & Reintam (2004), Kuht et al. (2012). A study from Krebstein et al. (2014) revealed that soil compaction also occurs on cultivated grasslands. It was found that after these areas had been trafficked, the bulk density, as well as the precompression stress increased. Although natural grasslands are used for cross-country movement the compaction and bearing capacity behaviour of these areas has not been as thoroughly investigated.

The strength of soil is influenced by bulk density, moisture content, texture and organic matter content (Lal & Shukla, 2004). The most compressible soil type is peat (van Asselen et al., 2009). Mineral soils that have high organic material content can have a contradictory influence on the compressive properties of soil (Keller et al., 2011). Moist soils are more susceptible to compaction than dry soils. In addition to soil properties, the degree of vehicle sinkage into the soil is also dependent upon the wheel load, tire width, inflation pressure and the number of passes (Botta et al., 2006). According to Soane (1980) a wheel's first pass compacts the soil more than the second or subsequent passes. However, this is also related to the initial soil density level (Botta et al., 2009).

In agricultural studies precompression stress (also called pre-consolidation stress) is often used as a standard measure of compressive strength, or as an indicator of the bearing capacity of soil (Keller et al., 2012; Alakukku et al., 2003). The precompression stress value is acquired through analysis of the stress-strain curve, which is determined using a uniaxial compression apparatus (oedometer). Precompression stress is the stress value between the elastic and plastic regions of soil behaviour (Alakukku et al., 2003). If the stress level on soil surface is lower than precompression stress the soil deformation is elastic and small. Higher stress values would cause plastic and larger deformations of soil (Lebert & Horn, 1991). The standard procedure for obtaining precompression stress is done using the graphical procedure developed by Casagrande (1936). However there are also other methods for determining precompression stress as well (Arvidsson & Keller, 2004). Cavalieri et al. (2008) demonstrated that choice of methods for calculating precompression stress is critical, and has a significant influence on the determination of the precompression stress values.

There have been a limited number of investigations into the relation between precompression stress and rut depth. Hemmat et al. (2014) concluded that, according to tests done with 3.2 t and 5.8 t tractors on calcareous unstable soil, it would be insufficient to consider the precompression stress itself as a universal threshold stress value for high and low sinkage. Moreover, their experiments have revealed that if the ratio of precompression stress to nominal ground pressure is smaller than 1.6, then the soil sinkage is irreversible and significant.

Up to this point, little research has been conducted on the variability of precompression stress values of Estonian soils, or on the rut depth formations left by vehicles moving cross-country. The first purpose of this study is to determine the precompression stress values of selected Estonian soils. The other primary aim is to investigate the relationship between precompression stress, and other characteristics of the stress-strain curves, and rut depths after one or more passes of wheeled trucks on different soil and land use types in Estonia.

MATERIALS AND METHODS

Based on the large scale Estonian soil map (Maaamet.ee), eight experiment sites were selected in order to assess the varying texture and soil moisture regime types. The map defines the soil texture types according to Katshynsky's classification criteria. The physical properties of tested soils are presented in Table 1. Three of the sites were located in areas of agricultural use (Kesa, KaimiI, KaimiII) while the other five sites were located on natural grasslands (LaevaI, Laeva II, Ilmatsalu, Sirvaku, Saverna). The experiments were carried out in 2013 and again in 2014 during the autumn and the spring when the moisture content of the soils were high. The areas were trafficked with a 7 t 2-axle truck that had a wheel load of 18 kN for the first wheel. At the Saverna site a 23 t, 3-axle, wheeled vehicle with a wheel load of 38 kN was used. The tires were inflated to pressure of approximately 6 bars for both test vehicles. With the exception of the Saverna and the Sirvaku test sites, the trafficking was done one time and then ten times over the same rut. At Saverna and Sirvaku only the one pass tests were conducted. The path over which the vehicles travelled was approximately 50–100 m long. The rut depth was recorded after the first pass and again after ten passes after every 1 m, or 5 m at the deepest part. In order to determine the contact area for nominal ground pressure, measurement were done on hard ground.

Table 1. Physical properties of tested soils: soil texture, organic matter (SOM) and gravimetric water content (w)

Site	Depth, cm	Clay, %	Silt, %	Sand, %	SOM, %	w, %
Sirvaku	0	1.4	32.3	66.3	4.0	50.5
	30	7.3	35.7	57.0	0.2	14.0
Kesa	0	7.8	30.7	61.5	1.3	25.9
	40	3.6	21.4	74.9	0.2	16.8
KaimiI	0	18.0	43.3	38.7	4.1	28.3
	30	18.1	63.5	18.4	1.1	39.0
KaimiII	0	0.4	67.8	31.8	15.9	72.4
	30	19.9	53.0	27.1	2.4	49.3
Saverna	0	11.1	20.2	68.7	1.9	27.5
	40	10.8	28.9	60.3	1.5	24.5
LaevaI	0	30.4	37.5	32.1	2.9	30.0
	35	26.3	39.0	34.6	0.6	21.3
LaevaII	0	20.9	48.8	30.3	4.9	38.6
	35	20.0	46.4	33.6	1.2	22.1
Ilmatsalu,	0	-	-	-	40.7	101.3
peat	20	-	-	-	31.6	94.5

Sand (2–0.063 mm), silt (0.063–0.002mm), clay (< 0.002 mm).

The undisturbed soil samples with cylinders (height 3 cm, diameter 10 cm) were collected right next to the ruts from topsoil, i.e. at depth of 0 cm, and from the subsoil. The subsoil layer refers to soil that is found at depths of 30 to 40 cm. This soil layer contains less organic material. The only exception to this sampling protocol was at the Ilmatsalu experiment area where the peat soil samples were taken at 0 cm and at 20 cm. Soil samples were compressed in an oedometer at sequential stresses of 25, 50, 100, 200, 400, 600 kPa. The compression time step was set to 30 seconds in order to reproduce the sudden loading situation of the field. After every stress step the compaction was recorded.

The precompression stress was determined according to the Casagrande procedure (1936). For these purposes a graph showing the compaction versus the logarithm of the applied stress was compiled from the measured data. From stress-compaction curve the point of greatest curvature must be identified. A suitable fitting curve must be used to accomplish this. The measured points of a stress compaction curve were fit via a fourth-grade polynomial and a logistic curve as suggested by Gregory et al (2006). The stress-compaction curve fit results are presented on Fig. 1. A comparison of the two types of fitting curves indicates significant difference in the shape of the stress-compaction curve.

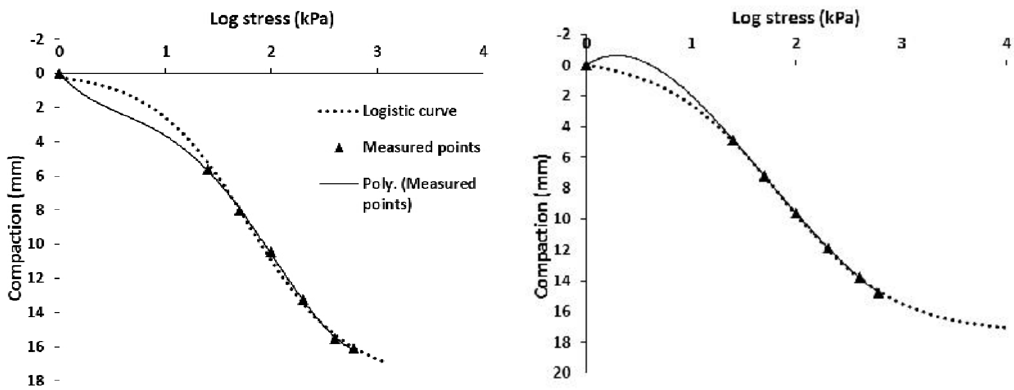

Figure 1. The logistic and fourth-grade polynomial fitting curves of the measured data.

The resulting fourth-grade polynomial curve is producing dependent upon the measured values underestimations or overestimations in compaction at lower stress levels (Fig. 1). It was found that the analytical calculation of the points of the greatest curvatures were in these cases outside the reasonable stress values (log stress from 0.8 to 3 kPa). For the present study 49 samples were measured and fitted with a fourth grade polynomial curve. In 27 of the cases the calculated points of the greatest curvatures were outside the reasonable region, or were even negative in some cases.

For the next step all of the measured stress-compaction curves were numerically fitted with a logistic function (1) and the parameters *a, b, c* and *m* were determined. For parameter *x*, a logarithm of pressure *p* in kPa units ($x = Logp$) and for a parameter *Y* compaction in millimetre units was used.

$$Y = a + \frac{c}{1 + \exp(b(x - m))} \quad (1)$$

The parameters of *a* and *c* of the logistic curve describe the extent of the curve in the direction of the compaction axis, with *m* determining the distance of the inflection point of the curve from the compaction axis, and the multiplication of *bc* determining the slope of the curve at the inflection point. The points of the logistic curve where its third derivate is zero determined the two points of its maximum curvature. The values of the pressure p_c and the logistic function Y_c at the point of the graph's maximum curvature can be calculated according to formulae (2) and (3) respectively:

$$Logp_c = m + \frac{1.317}{b} \quad (2)$$

$$Y_c = a + \frac{c}{4.732} \quad (3)$$

The measured experimental stress-compaction dependencies were fitted with logistic curves with a precision of R^2 that ranged from 0.97 to 0.99. The points of the maximum curvature were calculated according to the determined *a, b, c* and *m* values without any visual interpretation of curves. These points of maximum curvatures as distinctive analytically determined parameters of the measured soil samples were also applied towards the analysis of the experimentally measured rut depths of the same soils.

Two longitude values measured in centimetres were selected for the comparison of rut depths using logistic curve parameters that consisted of the values of logistic function Y_c at the point of its maximum curvature at the topsoil and subsoil layers. Two other logistic curve based parameters were also chosen in the units of longitude multiplied by pressure ($S = (Y_c p_c)/2$ and cm kPa units were used in calculations). These were also at the topsoil and subsoil layers. The latter unit is proportional to the work ($A = Fs$ or $A = p\Delta V$) done by the wheel in creating the ruts. On the stress-compaction graph this work is determined by the area between the logistic curve, the pressure axis and the perpendicular line from the pressure axis to the point of maximum curvature on the logistic curve. In order to simplify the calculations, this area was approximated by a triangle, and the logistic curve in the actual interval was replaced by a straight line. The area of this triangle is used as the parameter on the Fig. 3.

For the above described method the point of greatest curvature was calculated according the logistic curve parameters. This was also applied towards the determination of precompression stress. From the stress compaction curve, the point of greatest curvature is identified and at that point the tangent to the stress-strain curve was drawn. The bisector was plotted between the tangent and a horizontal line. Next, the virgin compression line (the straight portion of the stress-strain curve) was drawn. The point of intersection between the bisector and the virgin compression line determined the precompression stress value.

Microsoft Excel and the free software environment R (R Core Team, 2015) were used for the statistical analysis. The *t-test* was used to compare the difference between the precompression values.

RESULTS AND DISCUSSION

The measured rut depth values from the field and the precompression values are illustrated in Table 2.

After the initial passes of the main test vehicle the mean rut depths were similar for all of the tested sites, and ranged from 2.5–7.3 cm. Larger differences in depth occurred after repeated passages and averaged from 6.3 cm to 20 cm. The calculated nominal ground pressure values for the vehicles were 344 kPa for the 7 t truck, and 323 kPa for the 23 t vehicle. The 23 t vehicle produced remarkably deep ruts after first passage despite the fact that the nominal ground pressure and the inflation pressures of the tires were similar to the main test vehicle. This can be attributed to the higher wheel load of the second test vehicle. According to Arvidsson & Keller (2007) tire inflation pressure has a significant influence on soil stresses, as well as on the contact area and the topsoil, i.e. up to depths of 10 cm, wheel load plays a large role in subsoil stresses. As the first axle load of the 23 t vehicle was more than two times than that of the other test vehicle, it also sank more. Therefore, for further modelling of the relationship between rut depth and precompression stress the results from Saverna have been left out. This finding illustrates the importance of the bearing capacity of the subsoil layer.

Table 2. Measured rut depth values after 1 pass and 10 passes, and the calculated precompression values

Site	Rut depth, cm				Soil sampling depth, cm	Precompression stress, kPa	
	1 pass		10 passes			Repetitions	
	Mean	Max	Mean	Max		1.	2.
Sirvaku	4.4	8.0	-	-	0	13	20
					30	63	-
Kesa	3.0	3.3	8.4	11.0	0	14	20
					40	50	45
KaimiI	3.3	6.0	7.3	10.0	0	13	18
					30	63	79
KaimiII	2.5	6.3	6.3	12.3	0	18	8
					30	126	79
Saverna	15.6	21.2	-	-	0	13	13
					40	79	-
LaevaI	4.3	8.0	19.5	33.0	0	20	25
					35	178	199
LaevaII	6.7	10.0	20.0	24.0	0	10	8
					35	158	141
Ilmatsalu	7.3	18.0	13.4	28.0	0	20	18
					20	32	56

The comparison of precompression stress values from the subsoil and topsoil layers of all of the experiment sites indicate that statistically, the precompression stress was significantly ($P < 0.05$) higher for the subsoil layer. The precompression values for the topsoil layer are similar to all of the other measured soil and landuse types. The low variability of the precompression values of the topsoil layer can be associated with the high moisture content of the soils. It is apparent that if the majority of the soil pores are filled with water which is almost incompressible, then the soil texture and organic material content will not have a significant influence on the bearing capacity of the soil. For the subsoil layer the differences in precompression stress are higher and statistically significant ($P < 0.05$). The highest values were found in soils with very high clay contents, i.e. the soil of LaevaI. For the deeper layers the moisture content is lower and the properties of the soil particles have some influence on resistance to the stresses. The initial bearing capacity, however, decreases with repeated passes, especially for soils with higher clay contents and peat soils. The lowest precompression values for both layers of peat soil were found at the Ilmatsalu site.

The results from the experiments indicate that in moist soil the precompression value cannot be used as a predictor of rut depth. The contact stress of the test vehicles exceeded the precompression stress values of the tested soils by a huge margin, but the sinkage after the first pass was not large. As one pass rut depths depend on different soils, the precompression stress values of these soils ($R^2 = 0.002$) is less of a factor. The highest correlation ($R^2 = 0.402$) between the precompression stress of the subsoil layer and average rut depth occurred after ten passes. For this reason only the first parts of the logistic curves and linear model were used in following analysis. The following analysis was applied to the linear model, where a linear dependence between the two variables was assumed and afterwards analysed. The R^2 coefficient of determination was used as a tool to evaluate the proposed dependencies. In Fig. 2 the results show the dependence of the maximal and average rut depths after ten or one passes calculated according to the value of the logistic curve on its point of maximum curvature (Y_c).

A comparison of the R^2 values of the topsoil and subsoil layers from Fig. 2 indicates, that in every fourth case, the results are quite similar. In the graph that uses the subsoil data, the R^2 values for the average and maximal rut depths after one pass are about 30% higher than those of the topsoil data. Confluent ratio is also observable between R^2 values describing ruts depths after 10 passes, here the difference is less than 7% for average and 3% for maximal ruts depths. The highest value of the R^2 was 0.767 for the maximal rut depths after one pass. The R^2 value for average rut depths after ten passes had the smallest values. In both instances $R^2 = 0.2$. Equations for the trend lines in Fig. 2A and B are also rather similar. A comparison of the results presented in Fig. 2 allows us to conclude, that the calculated values of logistic functions at the points of their maximal curvature from the topsoil- or subsoil data may be used to predict one pass rut depths and the maximal depths after ten passes with equal success.

The results of the analysis based on the area on the stress-compaction graph are presented in Fig. 3.

Analysis, which was made on the basis of area, gives a different result based on the topsoil and subsoil data (Fig. 3A and B). Due to the large *m* values of the subsoils, there was a difference of ten times between the scale of the area on the stress-compaction graph and that of the topsoil data. The differences in the results of average rut depths after one pass ($R^2 = 0.221$ or 0.270) are not as striking, although in the case of the maximal rut depths of topsoil, the data showed a value of $R^2 = 0.444$ as opposed to the subsoil data which showed $R^2 = 0.135$ – a difference of more than three times. The significant difference is observable in the instance of average rut depths after ten passes: here the topsoil based data gives only $R^2 = 0.087$ while the subsoil data shows $R^2 = 0.746$, or approximately, an 8.5 times difference. The corresponding R^2 for the maximal values of the rut depths differ by about two times. Comparison of the R^2 values that are presented in Fig. 2 and Fig. 3 allows for the conclusion that in order to predict the rut depths after ten passes (either average or maximum) an area parameter from subsoil should be used.

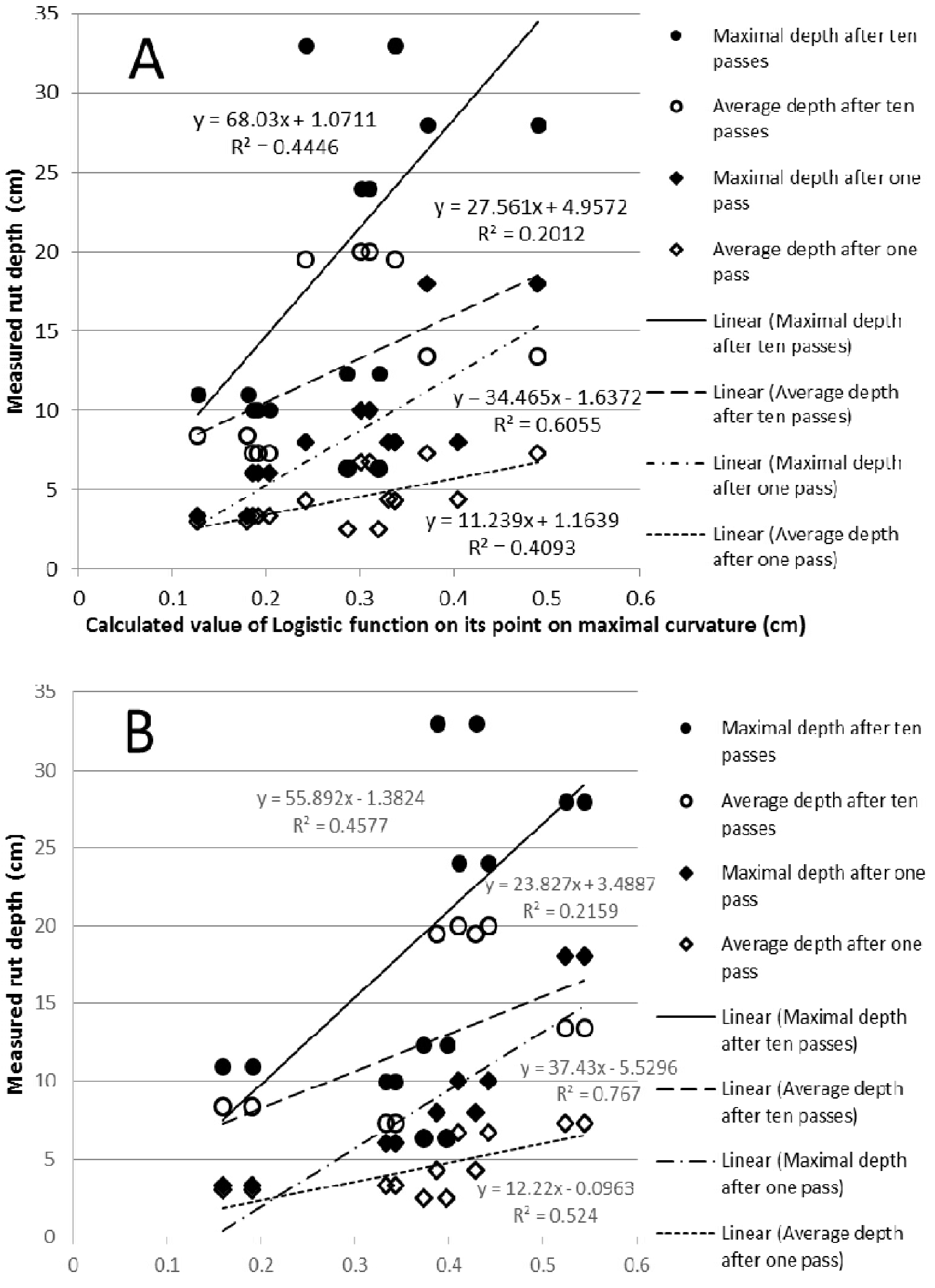

Figure 2. The dependence of the rut depths on the calculated values of the logistic function at the point of its maximal curvature according to the data from the topsoil layer (A) and the same dependence according to the data of the subsoil (B).

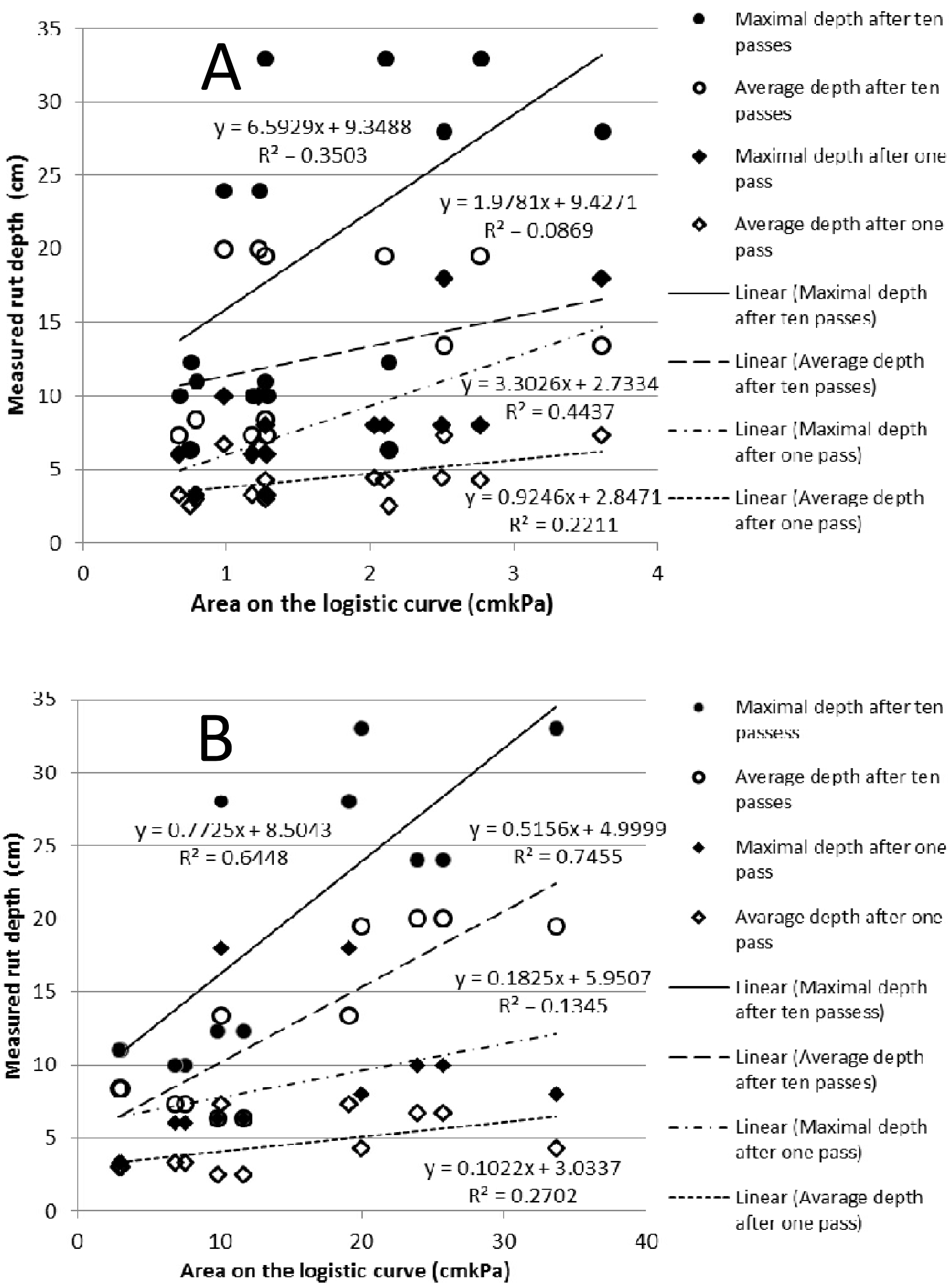

Figure 3. The dependence of the rut depths on an area on stress-compaction graph according to the data of the topsoil (A) and the subsoil (B) layers.

CONCLUSIONS

The precompression stress of topsoil at high moisture content in Estonia is more affected by water content than by other soil properties. In the subsoil layer the precompression stress is more dependent on the soil properties, but the initial high bearing capacity can decrease after repeated passes and deep ruts can form, such as is the case with soils with high clay contents. This study reveals that precompression stress cannot by itself be used as a threshold value to determine extent of sinkage.

Fitting experimental data to the stress-compaction graphs in order to determine the point of the maximum curvature led to the preference of the logistic curves. It was possible to calculate the points of maximum curvature analytically. The analysis allows to conclude that the calculated values of logistic functions at the points of their maximal curvature from the top- or subsoil data are equal in terms of predicting the average rut depths after one pass and the maximal depths after ten passes. For calculating rut depths for ten passes (average or maximal depths) subsoil data should be used with calculation based on the area on stress-compaction graph.

Nominal contact pressure is not the best indicator for determining vehicle sinkage. The results of this study indicate that the bearing capacity properties of the subsoil are more of a factor in rut depth formation than the topsoil properties are. Further investigation is needed to describe the relationship between precompression stress, and other characteristics of the stress-strain curves, and rut depth induced by vehicles with different weights.

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