DEVELOPMENT OF A PROTOCOL FOR ECOEFFICIENT WOOD HARVESTING ON SENSITIVE SITES (ECOWOOD)

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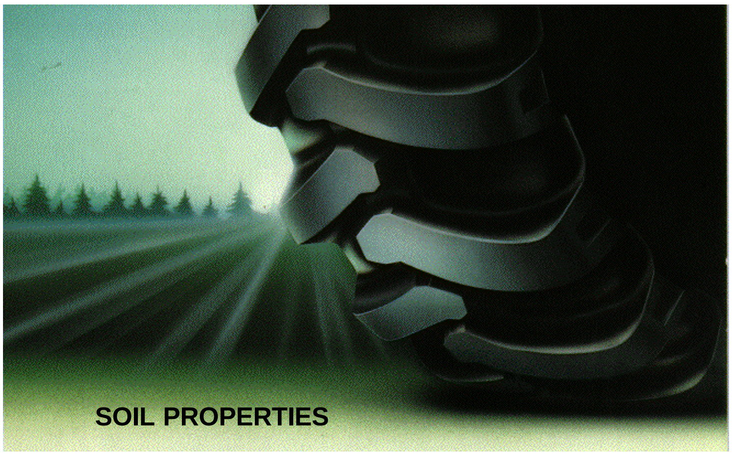
SOIL INTERACTION MODEL

APPENDIX REPORT No 8



MODELLING OF THE WHEEL AND SOIL

4. FOREST SOIL PROPERTIES

SURVEY ON FOREST SOIL PROPERTIES AND SOIL COMPACTION FOR STUDYING THE MOBILITY OF FOREST TRACTORS

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MODELLING OF THE WHEEL AND TYRE

4. FOREST SOILS

1. FOREST SOIL PROPERTIES

Forest soils as such present a huge variation in all the aspects and the property list is long. Three main disciplines are involved in soil researches are

- geology, the origin, the chemical and physical properties of the soil are of main interest
- soil science, the soil is considered as a growth medium for plants
- soil mechanics, soil is considered as a supporting medium for buildings or transport systems

1.1 Geology

The main classification from the geological point of view for the purpose of the study is the origin and structure of the soils. Generally three types can be distinguished

- alluvial soils, which are often deep deposits of rather homogenous soil particles
    - fine grained soils, clay soils, cohesive soils
    - coarse grained soils, sandy soils, friction soils
- moraine soils, which are mixtures of particles of different size. Moraine soils are often shallow, because the rock bottom is near the surface
- organic soils

Different soil classification schemes are presented, and the following existing classifications are practical for the purposes of the study

- NSR classification (Eriksson et al 1978), which is convenient for the Nordic soils. USCS (Unified Soil Classification System), which has been adopted by U.S. Army Corps of Engineering is widely used, and applicable rather universally. Also ASAE has adopted this classification.

1.1.1 Soil properties

Löffler (1979) presents the following classification matrix for soil moisture and density, Table 1.1 .

Table 1.1 Probable combinations of moisture content and soil dry density under natural conditions (Löffler 1979)

Soil dry Density		Moisture content								
		1	2	3	4	5	6	7	8	9
Class	kg/m³	<10%	10-19.9	20-29.9	30-30.9	40-40.9	50-50.9	60-60.9	70-70.9	>80%
1	600-790				x	x	x	x	x	x
2	800-999		x	x	x	x	x	x		
3	1000-1190	x	x	x	x					
4	1200-1390	x	x	x						
5	1400-1590	x	x							
6	1600-1790	x								
7	1800-1990									
8	2000-2200									

1.2 Soil Science

Soil science aims at describing the soil properties and variables, which are important in determining the growing potential of the substrate medium. In this context the main problem is connected to the engineering properties of the soil, and therefore the soil fertility/trafficability parameters are taken into consideration.

1.2.1 Site classification

In Finland so called Cajander site types are used as a site index. Cajander classes are based on vegetation analysis, because a strong correlation between vegetation type and production potential of the site has been found. Also a certain site class index (e.g. average height at a certain age) can be found for each forest site type.

As a rule, the site index increases as function of the share of fine particles, because the water and nutrient retention capacity of clays are high, see Table 1.2. For Calluna type (CT) the share of fine grained fraction is 3.4 %, but for richer herbaceous sites (OMT) the share is 12.1 %. On the others, the trafficability properties, such as higher soil moisture, lower soil density and higher share of humus of more productive sites give hints of lower trafficability. There are no larger studies concerning the mechanical properties (cohesion, internal friction, bearing capacity or compressibility) of different site classes, but forest site can be surely included in trafficability models. It gives a certain information on soil trafficability, but cannot be used as a sole soil parameter.

Table 1.2 Soil particle distribution of different site types (Westman 1990)

Soil fraction	Site type			
	CT	VT	MT	OMT
	Fraction, %			
Sand	35	48	26	34
Fine sand	61	30	43	30
Silt	2.9	4.7	8.1	8.4
Clay	0.5	2.2	1.5	3.7

The use of the occurrence of some plants can improve the screening out some site properties, which are somewhat correlated with trafficability. For example some Salix species indicates the occurrence of ground water outlets, or Pyrola rotundifolia the presence of clay-rich soil.

1.2.2 Soil horizons

Due to the weathering the bedrock deteriorates and the soil undergoes various changes over time and develops horizons. The intensity of the process varies with location. In the Finnish forest moraine soils the following distinct horizons are found, Table 1.3 This means, that the soil theories based on ideal soil models with infinite, homogeneous substrate are not always applicable, and different layered models, developed originally for road construction, may be more applicable, even they are more complicated.

Table 1.3 Average Finnish forest soil properties by different horizons (Westman 1990)

Horizon	Thickness, mm	Organic matter, %	Solid density, kg/m^3	Dry density, kg/m^3	Porosity, e_o
H	62	69	1450	150	90
A	98	4	2470	1050	57
B	200	5	2490	1110	56
C		2	2570	1340	48

The H-horizon is mainly composed of organic matters, and has very low strength and compressibility properties. Otherwise, it is some kind of transformation zone between vegetation and soil, and the biological processes, roots, microbes and nematodes, renovate it continuously.

1.3 Soil Mechanics

Soil cohesive and friction properties are clearly dependent on particle size, see Table 1.4.

Table 1.4 Soil properties (Kuonen 1983)

Property	Cohesive soils	=>		Friction soils	
	Clay	Claysilt	Silt	Fine sand	Sand
Granulometry, mm	< 0.002	< 0.06	< 0.02	< 3	< 6
Cohesion, kPa	25	20	0	0	0
Friction angle	22	27	33	34	38
Water content, %	47	25	32	17	13
Wet density, kg/m^3	1750	2000	1900	2000	1950
Dry density, kg/m^3	1190	1600	1439	1709	1726

2. SOIL PENETRATION RESISTANCE

2.1 Penetration resistance in assessing site properties

Because soil penetration resistance, or cone index, plays an integral part in the WES method, rather a covering literature survey on soil penetration has been carried out. Soil penetration resistance can be used as a soil input variable in assessing the wheel performance. Most of the studies on soil penetration resistance are concentrated on the assessing of the trafficability of soils.

It has been found, that increase in soil penetration resistance after wheel pass is often more pronounced than in soil density profile. Thus, by analysing soil penetration profiles some changes in soil properties can be assessed. Because root penetration is dependent on soil density, the comparison of penetration resistance in different layers can be used as one of the variables in assessing the damages to the soil due to the traffic.

Soil penetration profile can be used in soil identification. Main soil types, friction/cohesion/peat can be interpreted, as well as the layering of the soil.

Soil penetration resistance depends both on the properties of the cone and those of the soil.

2.1.1 Influence of penetration resistance on cone properties

Soil penetration resistance depends largely on cone area and angle and somewhat on penetration velocity. There are some studies on theoretical modelling of cone resistance, and also empirical studies where different cones are compared. In this report only the penetration resistance (q) measured using the ASAE standard penetrometer protocol and device is considered. In practice, it is equivalent to old concept of CI (Cone Index), which is expressed in Imperial Units (lb/sq.in). Penetrometer is widely used in terrain evaluation, and the literature references are abundant. As the penetration resistance in most soils is dependent on the penetration depth, penetration resistance curve contains detailed data on variation on soil penetration depth as a function of depth. For practical applications often the ***penetration depth at critical depth*** is used as the sole soil penetration resistance value. The recommended values for determining the critical depth are given in Table 2.1.

Table 2.1. Critical depth for different soil/vehicle combinations (after Farnell penetrometer)

	Loose dry sand	Reading decrease in depth (abnormal profile)	Reading increase or remain constant in depth	Peat, Muskeg
Wheeled vehicles				
Up to 22 500 kg	**0 ... 0.150**	**0.150 ... 0.450**	**0.150 ... 0.300**	*
Over 22 500 kg	0 ... 0.150	0.225 ... 0.525	0.225 ... 0.380	
Tracked vehicles				
Up to 1 500 kg		*		0 ... 0.150
1 500 to 4 000	0 ... 0.150	0.075 ... 0.380	0.075 ... 0.225	0.075 ... 0.225
4 000 to 7 000	0 ... 0.150	0.150 ... 0.450	0.150 ... 0.300	0.150 ... 0.300
7 000 to 11 000	0 ... 0.150	0.150 ... 0.450	0.150 ... 0.300	0.225 ... 0.380
11 000 to 45 000	**0 ... 0.150**	**0.150 ... 0.450**	**0.150 ... 0.300**	**0.380 ... 0.450**
Over 45 000	0 ... 0.150	0.225 ... 0.525	0.225 ... 0.380	*

Anttila (1998) found out, that the penetration resistance measured at 0.150 mm depth had the highest prediction power when developing rut depth modelling, see Figure 2.1. It coincides with the transition from A to B horizon in average Finnish moraine soils (Westman 1990). Therefore in Finland we have used the average penetration depth at 0.125 to 0.175 m depth as a critical depth.

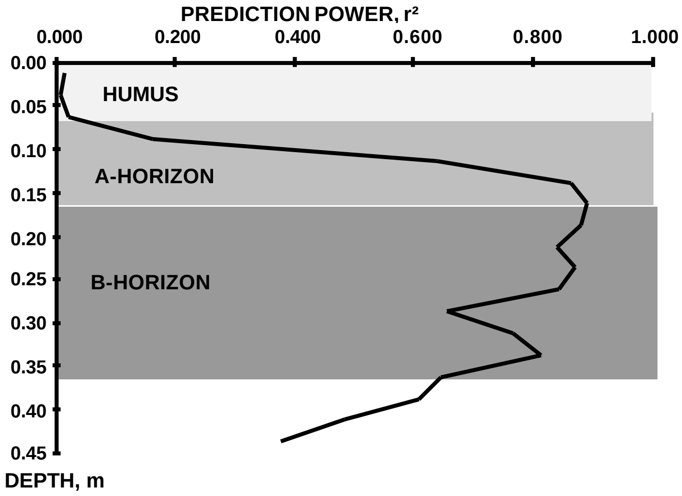


Figure 2.1. Correlation coefficient squared (=prediction power) as a function of sample depth. Different average soil horizons after Westman (1990).

2.1.2 Dependence of penetration resistance on soil properties

Soil penetration resistance depends on soil particles, density and air/water content, which also affects the root penetration. There are several studies on root growth or other biomass production as a function of soil penetration resistance.

2.1.3 Soil moisture

There are different practices in determining the soil moisture and expressing the results. Also the nomenclature varies, even in the field of soil engineering and soil mechanics. In forestry, mainly in soil science and peatland forestry, the variation in terminology increases the difficulty of comparing different papers.

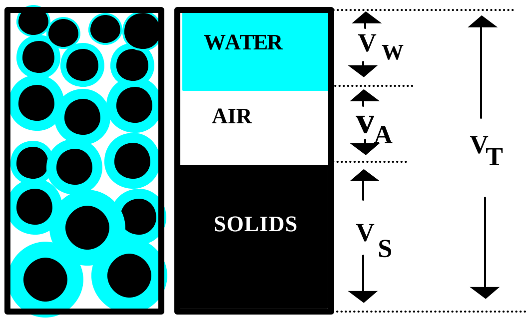


Figure 2.2. Soil composition

m_W	mass of water in sample, g
m_D	dry mass of sample, g
m_T	wet mass of sample, g ($m_T = m_W + m_D$)
V_T	volume of sample, m^3
V_W	volume of water in the sample, m^3, ($V_W = m_W/1000$)

(Soil) Moisture, general term to describe water/soil particle relation

MC_{DW}	Water content, Soil moisture content, dry weight basis is generally used in geotechnics, w/w
MC_{WW}	Soil wetness, soil water content, wet weight basis, used in peatland forestry
MC_{VOL}	(Soil) volume moisture (content), v/v
γ	soil dry density, g/m^3

The dependence between the different moistures are as follows:

$$MC_{DW} = \frac{m_W}{m_D} \cdot 100 \tag{2.1}$$

$$MC_{WW} = \frac{m_W}{m_T} \cdot 100 = \frac{m_W}{m_D + m_W} \cdot 100 \tag{2.2}$$

$$MC_{VOL} = \frac{V_W}{V_T} \cdot 100 = \frac{\frac{m_W}{1000}}{\frac{m_D}{\gamma}} \cdot 100 = \frac{m_W \cdot \gamma}{m_D \cdot 1000} \cdot 100 \tag{2.3}$$

$$MC_{DW} = \frac{100 \cdot MC_{WW}}{100 - MC_{WW}} \tag{2.4}$$

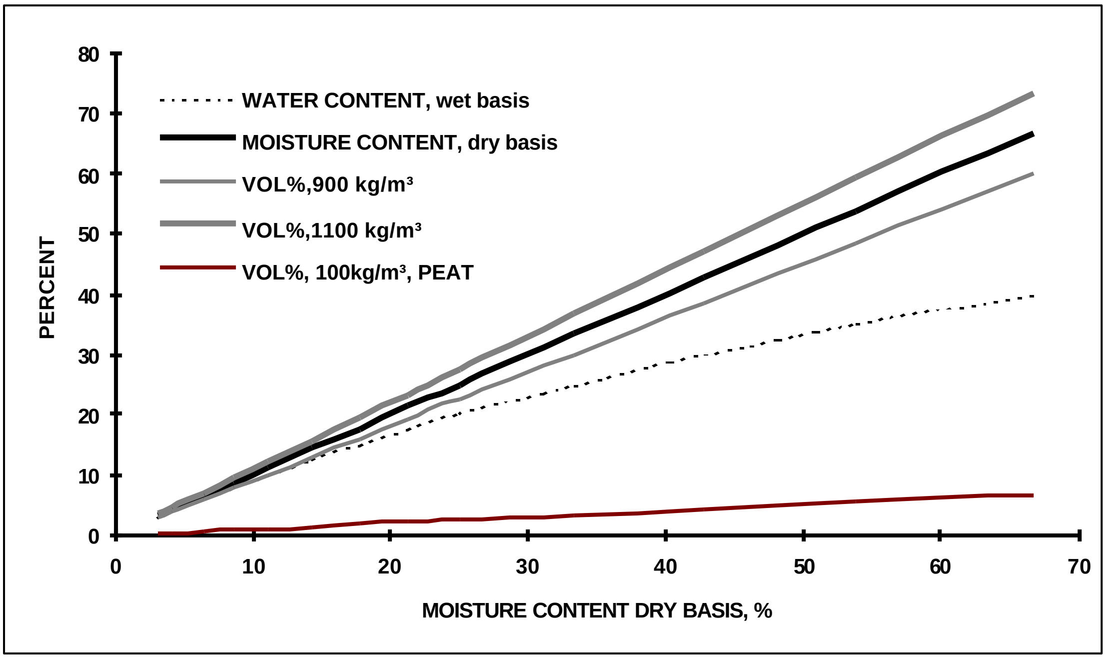
$$MC_{WW} = \frac{100 \cdot MC_{DW}}{100 + M_{DW}} \tag{2.5}$$

$$MC_{VOL} = \frac{MC_{DW} \cdot \gamma}{1000} \tag{2.6}$$

$$MC_{DW} = \frac{MC_{VOL} \cdot 1000}{\gamma} \tag{2.7}$$

The different moisture percentages are compared in Figure 2.2. Volume moisture and Moisture content are the same, if the dry density of soil dry mass is 1000 kg/m³. If the density is lower, then volume moisture is under moisture content. Normal density of the A-horizon is somewhat over 1000 kg/m³ and therefore TDR-measured moisture is often some kind of an overestimate. On peatlands, however, the correction is necessary.

As a conclusion, up to 20% levels the differences between expressed moisture percentages are rather small. On wetter conditions, and always on peatlands, it is important to pay special attention on soil moisture expressions.



MC%.XLS

Figure 2.2. Comparison of the different moisture percentages

The gravimetric and volumetric moisture contents for mineral soils are rather close to each others, and the models can be used with a certain caution using both gravimetric and volumetric moisture. The dry density of peat is usually very low, and therefore it is important to distinguish between volumetric and gravimetric moisture when estimating peatlands' properties.

2.2 Studies on penetration resistance on cohesion soils

There are several studies on soil penetration resistance, most of them having only water content as an input variable. Some researchers have constructed different one entry (MC) models for different soil types. Two and three entry models having clay content and/or soil density are also available.

2.2.1 Ayers & Perumpral (1982)

Ayers & Perumpral (1982) measured soil penetration resistance values in soil bin using artificial soils with varying packing degrees and clay content. They developed a universal model, Eq(2.8). The constant C1-C4 for different soils can be developed from field data using the best fitting technique. For the artificial test soils the constants are as given in Table 2.2. It seems, however, that the model gives too low a penetration value for the Finnish moraines.

$$\mathrm{q} = \frac{\mathrm{C1} \cdot g^{\mathrm{C4}}}{\mathrm{C2} + (\mathrm{MC} - \mathrm{C3})^2} \qquad (2.8)$$

where

q is penetration resistance, kPa
g soil dry density, g/cm³ (NOTE, soil density given in **g/cm³**)
MC moisture content, % dry weight
C1, C2, C3, C4 constant to be estimated depending upon soil type

Table 2.2 Constants for Ayers & Perumpral's model, Eq(2.8)

Soil type	Const1	Const2	Const3	Const4
100%Clay	4540,90	31,94	9,21	6,37
75%Clay-25%Sand	928,10	20,22	7,41	6,60
50%Clay-50%Sand	82,40	9,47	4,77	7,50
25%Clay-75%Sand	1,10	2,19	3,29	9,34
100%Sand	1,58	17,72	5,54	8,92

The Ayers & Perumpal model has an advantage to react with the true behaviour of soil a function of soil moisture, because after a certain moisture, optimum moisture, the penetration resistance declines with lowering moisture. For the Finnish climate and soils the model does not give any edge, because as a rule soils stay in wetter than optimum moisture state during the short dry spells.

2.2.2 Sitkei & Kiss (1986)

Sitkei & Kiss (1986) developed a model based on Ayers & Perumpral's model (2.9), applicable for the 0-depth layer of Hungarian soils. It seems to give too low values for low density moraines to be used as CI-value, but may be used to simulate the penetration resistance of the surface layer.

$$q = \frac{200 \cdot g^6}{20 + (MC - 8)^2} \tag{2.9}$$

q	penetration resistance at 0-depth, MPa
g	soil density, g/cm^3
MC	moisture content, %

2.2.3 Witney et al (1984)

Witney et al (1984) used cone penetration resistance as a variable for studying soil compaction on ploughed agricultural soils and developed the following semiempirical model for penetrating resistance, Eq. (2.10). This model seemed to have a certain matching with the field observations, see Chapter 2.3.

$$q = 1000 \cdot \left(15.92 \cdot C_r \cdot \exp^{-0.08 \cdot MC} + 0.0000258 \cdot \gamma \cdot \exp^{\frac{\pi}{1+C_r}} \right) \tag{2.10}$$

where

q	penetration resistance, kPa
C_r	Clay ratio, (clay/other components)
MC	soil moisture content, % (w/w)
γ	soil density, kg/m^3

2.2.4 Elbanna & Whitney (1986)

Elbanna & Witney (1987) went on with the development of the penetration resistance in agricultural soil, Equation (2.11). For an unknown reason, their model seems to give overestimates for the Finnish forest moraines.

$$q = \left(3.62 \cdot C_r \cdot e^{\frac{-0.1 \cdot MC}{1+C_r}} + \frac{0.000065 \cdot g}{1 + 2 \cdot C_r} \right) \cdot e^{\frac{p}{1+2 \cdot C_r}} \tag{2.11}$$

q	penetration resistance, MPa
C_r	Clay ratio, (clay/other components)
MC	soil moisture content, % (w/w)

γ soil density, kg/m^3

Their simpler model is

$$q = \frac{450.5}{MC^2} + 0.000186 \cdot g \qquad (2.12)$$

2.2.5 Freitag (1986)

Freitag (1987) presents some old WES-data, of which the following cone index equations as a function of soil moisture can be developed for fine grained soils (Eq(2.13 a-d). They can be considered as some kind of minima for wetter moraines.

CLAY	$\mathrm{CI} = \exp^{(10-0.1MC)}$	(2.13a)
SILTY CLAY	$\mathrm{CI} = \exp^{(11-0.2MC)}$	(2.13b)
SILT	$\mathrm{CI} = \exp^{(12-0.3MC)}$	(2.13c)
SANDY SILT	$\mathrm{CI} = \exp^{(13-0.4MC)}$	(2.13d)

2.2.6 Hinze (1990)

Penetration resistance depends on the soil moisture and the share of fine grained particles. After Hinze (1990) the dependence of the penetration resistance on the soil moisture for different soils are as given in Equations (2.14-2.16). The original linear models are Equations (2.14a-2.16a), and later developed non-linear models, based on the data in Equations (2.14b,2.15b). Non-linear equations seems to fit better for the observations, but cannot be extrapolated under or over the data moisture range, 14 to 40 % for sandy silt and 18 to 26 % for silty sand.

Sandy silt 1

$q = 2872 - 61 * MC \quad MC = 14 - 40\ \%$ (2.14a)

$$q = 73500 \cdot MC^{-1.28} \qquad (2.14b)$$

Sandy silt 2

$q = 2520 - 53 * MC \quad MC = 14 - 40\ \%$ (2.15a)

$$q = 30000 \cdot MC^{-1.01} \qquad (2.15b)$$

Silty sand

$q = 1720 - 22.6 \cdot MC \quad MC = 18 - 26\ \%$ (2.16a)

2.2.7 Pulp and Paper Institute model

A model developed by Pulp and Paper Research Institute of Canada is as follows, Equation (2.17)

$$q = 6.89 \cdot \exp(6.464 - 0.0506 \cdot MC) \qquad (2.17)$$

2.2.8 Perdok & Kroesbergen (1999)

Perdok & Kroesbergen (1999) developed the following model for penetration resistance of different artificial soil types after laboratory testing, Eq(2.18). The suitability for terrain conditions is not yet verified, however.

$$q = 1000 \cdot e^{a_0 + a_1 \cdot PV + (a_2 + a_3 \cdot PV) \cdot MC} \qquad (2.18)$$

where

q is soil penetration resistance, kPa

a_0, a_1, a_2 a_3 coefficients from Table 2.3

PV pore volume, %

MC moisture content, %

Table 2.3 Coefficients for Perdok & Kroesbergen (1999) penetration resistance model, Eq(2.18)

Soil type	a_0	a_1	a_2	a_3
Sand	4.3715	-0.0834	-0.1426	0.0017
Loam	4.7853	-0.0791	-0.1719	0.0021
Clay	4.8878	-0.0688	-0.1539	0.0018

2.2.9 Sullivan (1999)

Sullivan (1999) gives a graph, of which the following model has been developed, Eq(2.19).

$$q = 2094903 \cdot MC^{-2.892} \qquad (2.19)$$

2.2.10 Anderson (1983)

For rated cone index (RCI) Anderson (1983) gives the following general model, Eq(2.20):

$$\ln(RCI) = 4.605 + \frac{2.123 + 0.008 \cdot C_{\%} - 0.693 \cdot \ln(MC)}{0.0149 + .002 \cdot C_{\%}} \qquad (2.20)$$

where

RCI is	rated cone index
C%	clay content, % of dry weight
MC	moisture content, % dry weight

Even rated cone index and cone index differ from each others in many respects, a simple equivalence is often used (see for example Larminie 1992)

$$\mathrm{CI} = \frac{\mathrm{RCI}}{0.8} \qquad (2.21)$$

2.2.11 Dexter et al (1988)

Dexter et. al (1988) studied some Australian soils and presents the following general model with some empirical constants, Eq(2.22):

$$q = \exp^{(k + m \cdot \gamma + n \cdot w)} \qquad (2.22)$$

where

q	penetration resistance, MPa
k,m,n	constants from Table 2.4
γ	soil density, t/m^3
w	soil water content, % (w/w)

Table 2.4. Coefficients for model (2.22)

Soil type and layer	K	m	n
Light clay loam, 0-50 mm	-7.3	6.0	-0.105
Loam, 50-250 mm	-6.2	6.0	-0.105
Clay loam, 250- mm	-4.2	6.0	-0.105
Sandy loam, 0-50 mm	-6.3	5.0	-0.061
Sandy loam, 50- mm	-4.8	5.0	-0.061

2.2.12 Murfitt et al (1975)

Murfitt et al (1975) studied the road construction over Canadian muskeg, and give the following model for organic silt soils. (MC w/d)

$$q = 1.49 \cdot 10^{8} \cdot \left(MC + 50\right)^{-2.79} \tag{2.23}$$

This model seems to match quite well with the Finnish moraine data.

2.2.13 Sojka et al (2001)

Sojka et al (2001) studied in situ penetration resistance, bulk density and water content relationship in silt loam. He found out that the dependence of penetration resistance from gravimetric moisture content and soil density is different in different depths. He gives the following models for soil penetration resistance, Tables 2.5 and 2.6.

Table 2.5. Two entry penetration equations with corresponding constants after Sojka et al (2001)

Depth, m	Equation	a	b
0.150-0.300	$q = a \cdot MC^{b}$ (2.24)	0.0003	-3.16
0.300-0.450	$q = a + b \cdot MC$ (2.25)	11.8	-0.37
All	$q = a + b \cdot MC$ (2.26)	0.78	0.23

Table 2.6. Three entry penetration equations with corresponding constants after Sojka et al (2001)

Depth, m	Equation	a	b	c
0.150-0.300	$q = a + b \cdot MC^{-1} + c \cdot g$ (2.27)	-2.29	66.6	-0.56
0.300-0.450	$q = a + b \cdot MC^{-1} + c \cdot g$ (2.28)	-1.44	117	-0.42
All	$q = a + b \cdot MC + c \cdot g$ (2.29)	-12.1	-0.11	10.9

where

q penetration resistance, MPa
MC gravimetric water content, g_w/g_s, decimal NOTE
γ bulk density, Mg/m^3 NOTE

2.2.14 Perumpal (1987)

Perumpal (1987) presents a review on cone penetrometer applications, and mentions that several both logarithmic and linear soil moisture/penetration models are presented by different authors, giving as an example the following model, Eq(2.30)

$$q = 4527.75 - 137.09 \cdot MC \tag{2.30}$$

MC gravimetric moisture content, in percentage

2.2.15 Vaz et al (2001)

Vaz et al (2001) have developed a new type of penetrometer, which combines also a TDR-coil, making possible to record simultaneously penetration resistance and volumetric soil moisture. Based on their test data, they give the following models for silt clay soils, Eq.(2.31).

$$q = a \cdot \frac{g^{n}}{g_{s}} \cdot e^{-b \cdot MC_{VOL}}$$

(2.31)

where

a, n, b soil specific constant, Table 2.7

γ bulk density, g/cm³ **NOTE**

γ_s specific gravity of solids, 2.65 g/cm³

MC_{VOL} volumetric water content, cm³/ cm³, decimal NOTE

Table 2.7. Constants for Eq(2.31).

Constant	a	n	b
Value	170.15	3.22	5.99

The model can be written simply

$$q = 17015 \cdot \frac{\left(\frac{BD}{1000}\right)^{3.22}}{2.65} \cdot \exp^{\left(-5.99 \cdot 10^{\prime\prime 5} \cdot MC \cdot BD\right)} \tag{2.32}$$

2.2.16 Hernanz et. al (2000)

Hernanz et. al studied the influence of cone size and different soil parameters to the bulk density parameters and developed the following models for predicting soil density profile based on soil penetration profile. The following models, Eq(2.33) and (2.34) are for standard cone.

a) soil penetration profile

$$\gamma = 0.913 \cdot q^{0.096} \cdot z^{-0.061} \tag{2.33}$$

b) soil penetration profile and water content

$$\gamma = 0.753 \cdot q^{0.096} \cdot z^{-0.072} \cdot MC^{0.092} \tag{2.34}$$

where

γ	soil bulk density, Mg/m³ (NOTE UNITS)
q	penetration resistance, kPa
z	depth, cm (NOTE UNIT)
MC	moisture content, % w/w

2.3 Comparison of the cohesion soil models

2.3.1 Penetration resistance and soil moisture in Finnish moraines soils

During the field tests to develop rut models for forwarder (Anttila 1999, Rantala 2000, Saarilahti et al 2002) some data on soil moisture and penetration resistance were collected from Finnish moraine soils. The following one-entry models were developed from the field observations, Eq(2.35 and 2.36). It is to note, that for a certain observations soil density is only an educated guess.

Gravimetric moisture

$$q = 3259 \cdot MC_{w/w}^{-0.386} \qquad r^2=0.241 \tag{2.35}$$

Volumetric moisture

$$q = 3358 MC_{v/v}^{-0.412} \qquad r^2=0.251 \tag{2.36}$$

The scatter diagram of the data with the models are given in Figure 2.3.

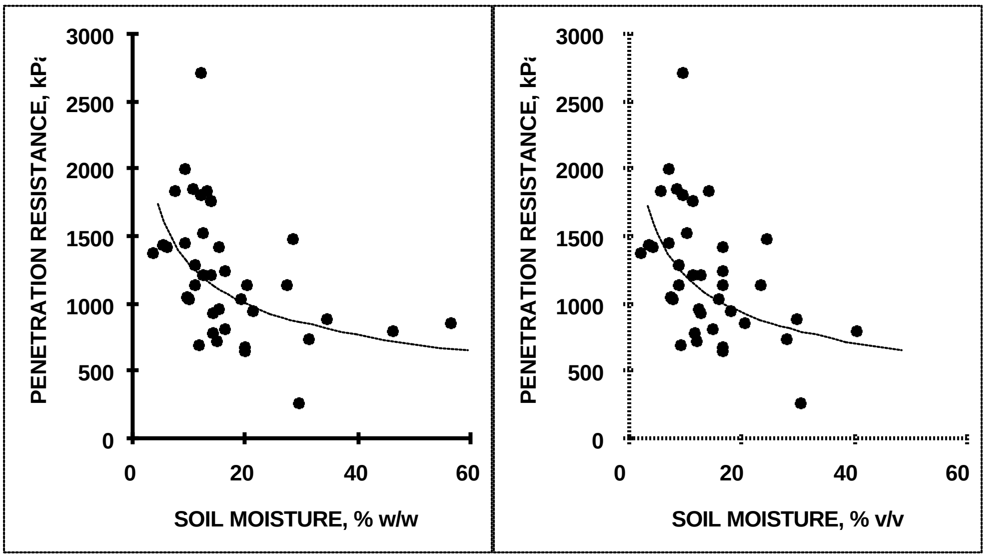


Figure 2.3. Soil penetration resistance as a function of soil moisture.

Fitting the Ayers & Perumpral's (1982) general equation, Eq(2.8) into Anttila's data showed that bulk density did not enter into the model, moisture being the only statistically significant variable. The model using volumetric moisture is

$$q = \frac{7137}{\left(20 + (MC - 10)^2\right)^{0.431}} \quad r^2=0.531 \qquad (2.37)$$

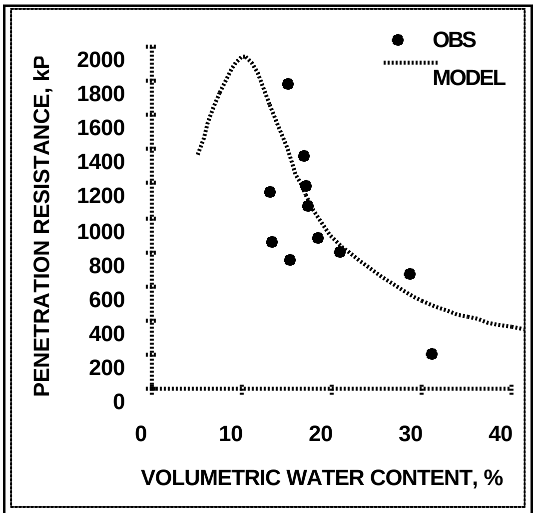


Figure 2.4. Penetration resistance as a function of moisture content in Anttila's data.

2.3.2 Applicability of the available models for the Finnish conditions

Most of the models presented in the literature are based on rather homogenous alluvial agricultural soils with no root mat or stones which are a typical features for the Finnish moraines. It is, however, interesting to try to pick out some models, which can be used in further simulations for developing different models for ecoefficient forwarding. It is evident, that the small data does not permit to point out the best model, but the exercise gives some light, that some of the models may give rather reliable estimates for the first stage of developing more comprehensive models. Different models are compared with the above mentioned data (Chapter 2.31), and the results are depicted in Appendix 2. Here some general observations are discussed.

Witney et al (1984) model (Eq.2.10) seems to fit rather well with the observed range. The only problem is that clay content is not normally known. Prior to larger empirical data it seems, that the model can be used in simulations for the Finnish conditions. The apparent discrepancy, for example rather a high observed penetration resistance for more moist soils is partly due to the influence of stones in the moraine soils. The Witney et al. model can be considered to represent the strength of the soil mass, and stones are some kind of addition to the penetration resistance. Thus, if the stoniness index is high, then the soil penetration resistance may be higher, and the risks for deep ruts diminishes.

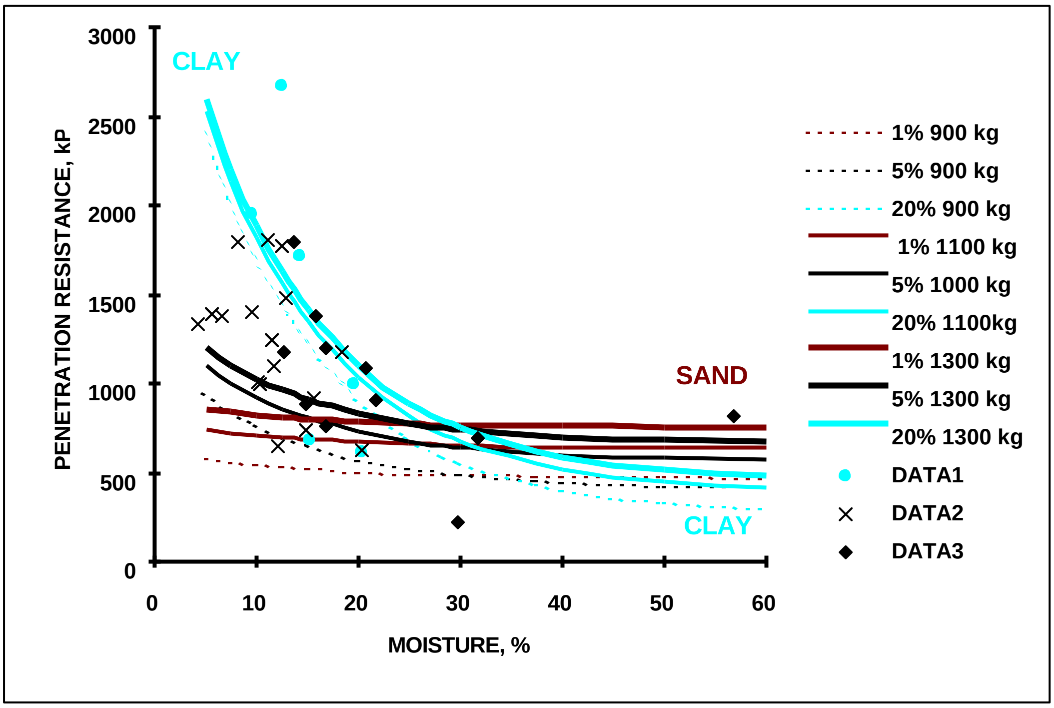


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Figure 2.5 Data1 (Rantala 2001, clay), Data2 (Rantala 2001, granular soils) and Data3 (Anttila 1994, silty soils) compared to Witney et al model, Eq(2.10).

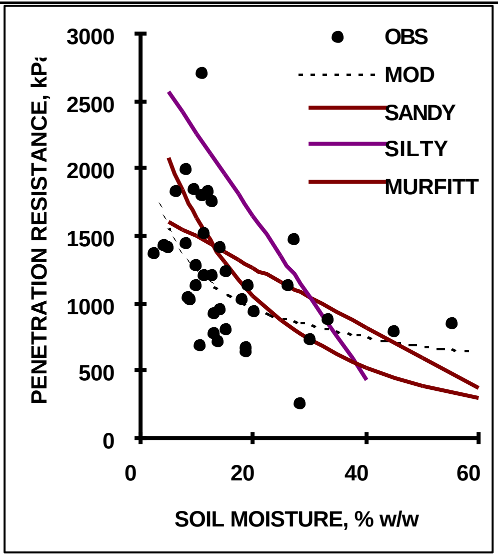

Figure 2.6 Murfitt et al (1975) and Hinze's (1990) models tested against the field data

Hinze (1990) developed his models from the data collected in Northen Germany, and the models seem to have a certain applicability to the Finnish forestry, see Figure 2.6, even the observed values are systematically lower than the estimates. Hinze's models can be used as some kind of maximum estimate.

Murfitt et al (1975) model seems to have the best matching with the observations, taking into account, that the data may contain occasional stones or roots. When comparing Hinze's models with the others' ones (Figure 2.6) we can find that his models gives a certain maximum.

After most of the models the penetration resistance is asymptotically dependent on soil moisture, see Figure 2.7. Generally soils have high penetration resistance if the moisture content falls below 20%. Evidently the threshold moisture between good and poor trafficability depends on soil properties, and for most soils the small variations around the threshold moisture influences largely on trafficability.

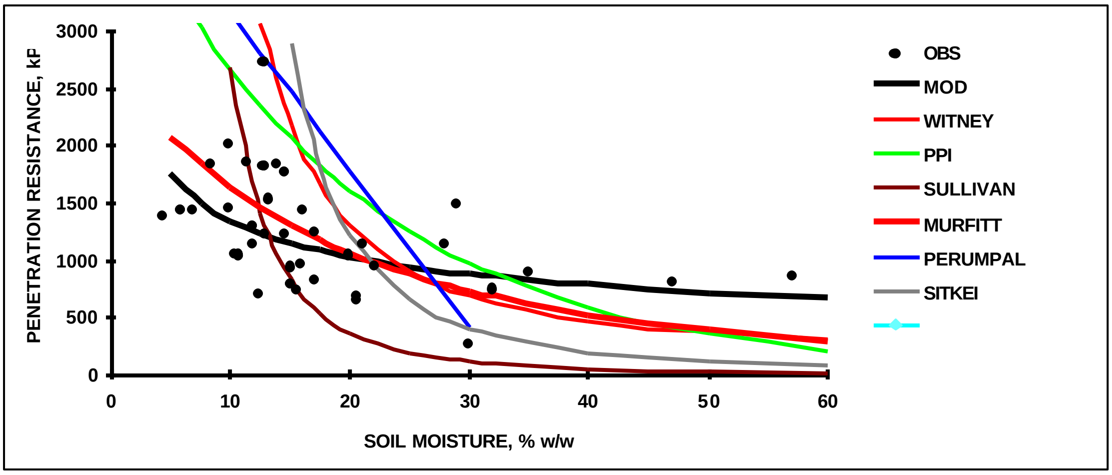

Figure 2.7 Penetration resistance as a function of soil moisture after different models compared to observations.

2.4 Penetration resistance of peaty soils

2.4.1 Penetration resistance models

The shear strength of the raw peat is great due to the high tensile strength of the fibres, but the penetration resistance and the bearing capacity are low, because of the low bulk density of raw peat. The penetration resistance increases as a function of humification degree, because as a rule the bulk density is directly correlated with humification degree, but the correlation with moisture content is inverse. The penetration resistance of peat can be estimated using Amarjan's (1972) model, Eq. (3.14a and 3.14b).

$$q = \frac{2500}{w} \cdot (100 - 1.4 \cdot R) \tag{2.38a}$$

$$q = \frac{2500}{w} \cdot \left(100 - 3.60 \cdot H^{1.414}\right) \tag{2.38b}$$

where

q on	penetration resistance, kPa
w	water content of peat, %
R	decomposition percent, % (Standard of the USSR)
H	v. Post humification class (Used in Nordic countries)

The following penetration resistance models, Eq(2.39) and Eq(2.40), as a function of peat moisture were developed from the data collected during the field tests:

Gravimetric moisture

$$q = 22172 \cdot \mathrm{MC}_{\mathrm{w/w}}^{-0.700} \qquad r^2=0.407 \tag{2.38}$$

Volumetric moisture

$$q = 23062 \cdot \mathrm{MC}_{\mathrm{v/v}}^{-1.287} \qquad r^2=0.283 \tag{2.40}$$

The scatter diagram of the data with the models are given in Figure 2.8.

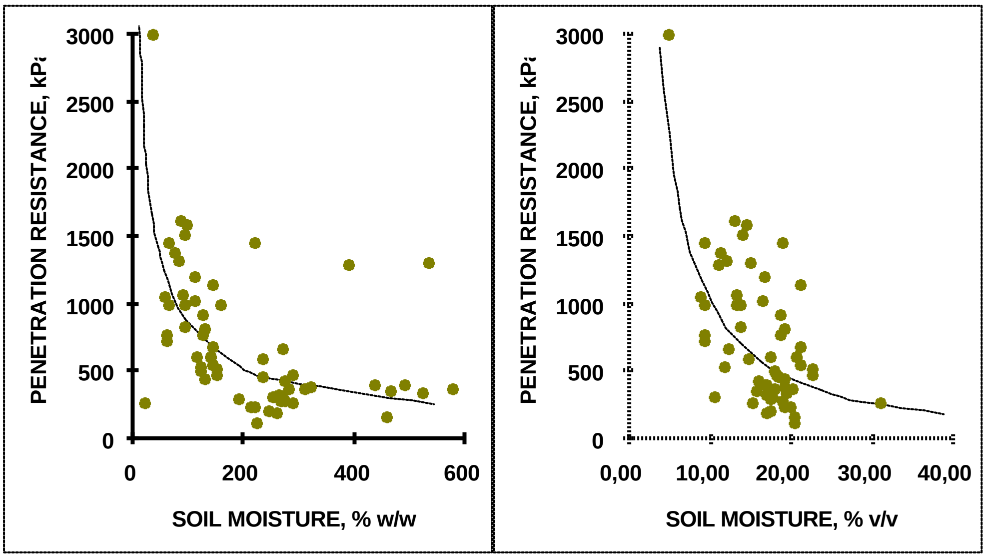

Figure 2.8 Peat penetration resistance as a function of soil moisture

2.4.2 Testing of the peat penetration models

Amarjan's (1972) model is tested against the field data collected during the field tests (the Finnish data). Unfortunately the peat properties (humification or others) were not recorded. The results are presented in Figure 2.9. The observations from shallow peaty depressions (SHALLOW) and true peatlands (DEEP) fit fairly well with the model results. Some remarkable deviations may be due to stones or trees in the peat or other anomalies.

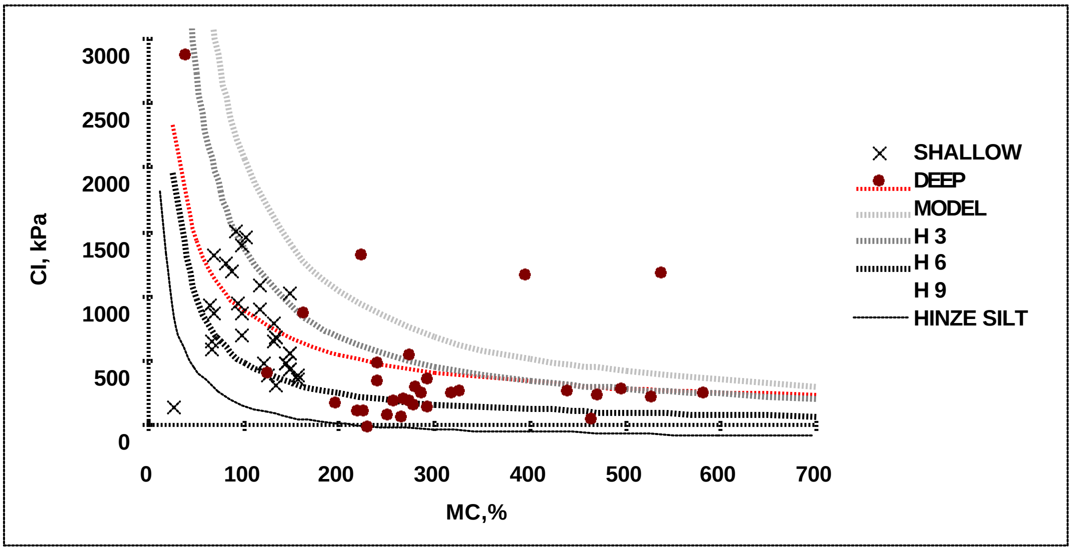

Figure 2.9 The observed penetration resistance (the Finnish data and Eq. x.x) as a function of the gravimetric moisture content compared to Amarjan's (1972) penetration resistance models and Hinze's (1990) silt model.

O'Mahony et al (2000) studied peatlands properties during the road construction programme. The fitting the Amarjan's model with this Irish data is depicted in Figure 2.10. It can be seen, that the medium humification curve is close to the observed penetration.

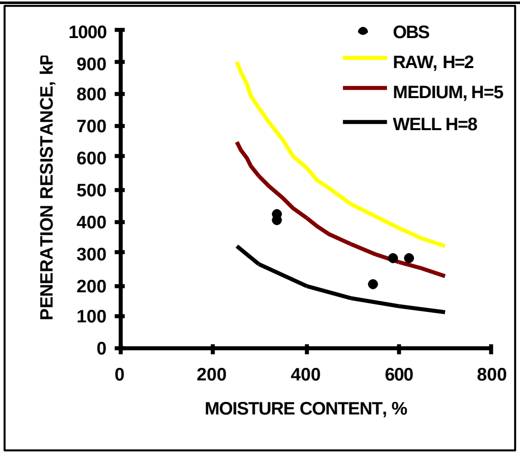

Figure 2.10 Fitting the Amarjan's model into the Irish data

3. SOIL SHEAR STRENGTH

Soil shear strength follows the well known Coulomb's formula

$$\tau = C + p \cdot \tan\phi \qquad (3.1)$$

where

τ soil shear strength, kPa
C cohesion, kPa
p load, kPa
ϕ soil friction angle, °

3.1 Measuring of the soil shear strength

Soil shear strength can be measured using different test apparatus, and the results are very dependent on the soil loading conditions and measuring methods.

- triaxial tests
- direct shear

Triaxial test are generally laboratory tests to assess the cohesion and friction component of the soils under different loading conditions. In direct shear tests soil reactions are recorded under vertical load only.

Vane tester is one of the most used devices to record direct shear of soil in situ conditions, even it is used also in some laboratory methods. Vane tester consists of a metal rod, with shear wings, which are pushed into the soil to a certain depth. The rod is turned using a recording torque meter, and the torque is recorded. In simpler versions, only the maximum torque is read. Based on that, soil maximal shear strength, soil vane strength is calculated.

More sophisticated versions permit the recording of the torque as a function of turning angle, making possible to establish soil deformation modulus.

3.2 Vane test

Vane tester is a simple device to asses the soil shear strength. It measures the unconfined shear strength of soil, soil cohesion. Therefore it is suitable for assessing the properties of cohesion soils.

3.2.1 Mineral soils

3.2.2 Peat

Amarjan (1972) gives the following model for estimating the peat shear strength as a function of moisture content and peat decomposition percentage when using a vane tester, Eq.(3.2)

$$\tau = \frac{140}{\mathrm{MC}} \cdot \left(100 - 1.1 \cdot \mathrm{R}\right) \qquad \text{(3.2 a)}$$

of which the following model, Eq(4.x b) can be developed for v Post's peat humification classes

$$t = \frac{140}{MC} \cdot \left(100 - 2.83 \cdot H^{1.414}\right) \qquad \text{(3.2 b)}$$

where

τ is	shear strength, kN/m² (kPa)
w	water content of peat, %
R	humification percent, % (Standard of the USSR)
H	v. Post decomposition class (Used in Nordic countries)

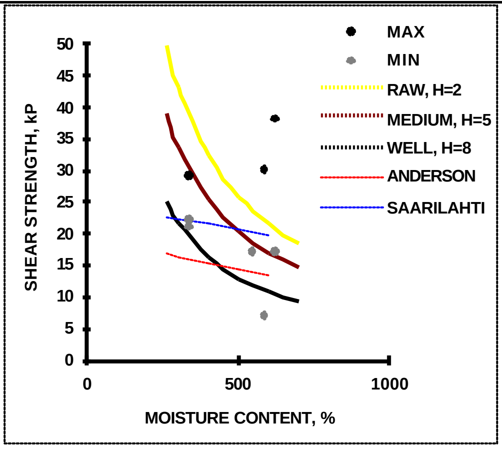

Figure 3.1 Peat shear strength in the Irish data as a function of moisture content compared to different models.

The Amarjan's shear strength model is tested with the O'Mahony et al (2000) peat data (the Irish data) in Figure 3.1. The data contains a certain range (Min, Max in Figure 3.1.) for a certain water content. It seems, that the minimum values have a certain fit with the Amarjan's model, Eq(3.2) when using medium-well decayed peat. Saarilahti's (1980) model also has a certain fit with the minimum values, but Anderson & Hemstock's (1959) model gives too low estimates. Figure 3.2 also shows, how important it is to know the peat decomposition degree.

Anderson & Hemstock (1959) model, Eq(3.3) for Canadian peat is

$$\tau = 19{,}3 - 0.01 \cdot MC \qquad (3.3)$$

Saarilahti (1980) developed the following model, Eq(3.4)

$$\tau = 24.7 - 0.0082 \cdot MC \qquad (3.4)$$

3.3 Dependence between penetration resistance and shear strength

3.3.1 Mineral soils

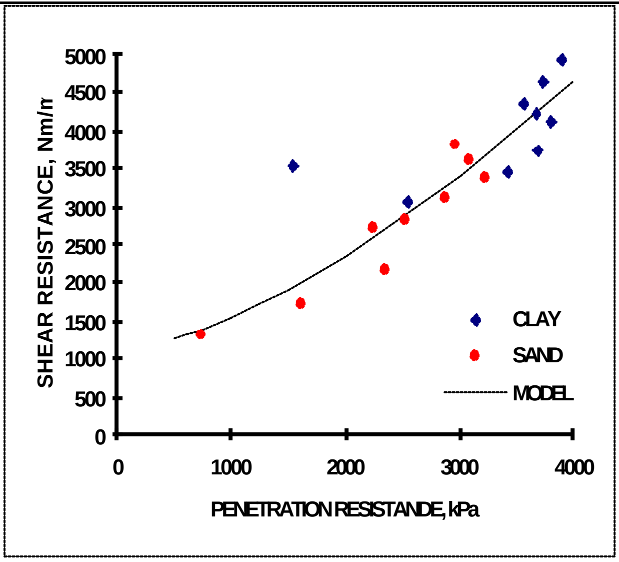

Figure 3.2 Soil vane shear strength as a function of soil penetration resistance (Meek 1996).

The data of Meek (1996) permits to establish the following dependence between the penetration resistance and soil shear strength, Figure 3.2. The developed dependence models are as given in Eq(3.5) and Eq(3.6):

$$\tau = 1100 + 0.00616 \cdot q^{1.6} \qquad (3.5)$$

$$q = -16300 + 2376 \cdot \ln(\tau) \qquad (3.6)$$

where

τ vane shear strength, Nm/m²

q penetration resistance, kPa

Trafficability Research team (1961) has obtained the following relationship between the cone index and shear strength

dry loess soil	$CI = 2 \cdot \tau$	(3.7)
moist loess	$CI = 3.3 \cdot \tau$	
dry sand	$CI = 4 \cdot \tau$	

3.3.2 Peat

Assuming that there is a certain dependence between peat penetration resistance and shear strength ($q = a_q \cdot \tau$) we can combine the two Amarjan's equations (3.8) and (3.9)

$$\frac{2500}{\mathrm{MC}}\cdot(100-1.4\cdot \mathrm{R}) = \mathrm{a}_{\mathrm{q}}\cdot\left(\frac{140}{\mathrm{MC}}\cdot(100-1.1\cdot \mathrm{R})\right)$$

and solve the coefficient a_q. We get the model, Eq(3.8)

$$\mathrm{a}_{\mathrm{q}} = \frac{17.87-0.25\cdot \mathrm{R}}{1-0.011\cdot \mathrm{R}} \qquad (3.8)$$

By letting the dependence between humification degree and decomposition percentage

$$H = 0.513\cdot R^{0.707} \qquad (3.9\ )$$

$$R = 2.57\cdot H^{1.414} \qquad (3.10)$$

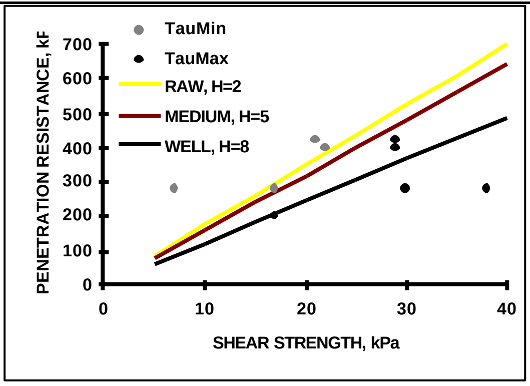

Figure 3.3 Dependence between peat shear strength and penetration resistance in the Irish data

we obtain the coefficient aq for v Post’s classes

$$a_q = \frac{17.85-0.643\cdot H^{1.414}}{1-0.0283\cdot H^{1.414}} \qquad (3.11\ )$$

It seems, that some kind of matching exists between the shear strength and the penetration resistance.

4. SOIL BEARING CAPACITY

In forestry soil bearing capacity is usually considered as maximal allowable wheel contact pressure. The actual wheel contact pressure, however, is difficult to assess, because the true contact area depends on tyre and soil properties. In most cases the soil bearing capacity must be taken as some kind of guideline only.

4.1 Soil bearing capacity modelling

In WES-method soil bearing capacity is included into soil cone index variable, and soil penetration resistance is used as a sole soil parameter. Different interpretations, such as MMP has been introduced for wheel site matching, see Appendix report No 5.

Because soil bearing capacity is largely dependent on soil cohesion and soil internal friction, some modelling of soil bearing capacity can be based on soil cohesion and friction models.

For friction soils the bearing capacity as such is not the limiting factor, but the shear strength. The wheel must develop enough friction between the tyre and soil in order to overcome the rolling resistance and other resistance forces, which grows high under larger sinkage in loose soils.

For cohesion soils (Saarilahti 1978)

$$Q_u = 2 \cdot C \qquad (4.1)$$

where

Q_u is soil bearing capacity, kPa (kN/m²)
C soil cohesion, kPa

which means that the contact pressure can be twice the soil cohesion, e.g. for example soil shear strength measured by vane tester.

4.2 Empirical values for estimating the soil bearing capacity

In the Table 4.2 the bearing capacity values of different soils has been collected from different authors. For the comparison the following ground pressure values (see Appendix Report No5 [1]) are given for a 12 t forwarder with 10 t full load. 400 kPa tyre inflation pressure is used in modelling, Table 4.1. The ground pressure is calculated using Ziesak & Matthiess (2001) model.

Table 4.1 Tyre ground pressure index for the reference forwarder

Tyre	Load size			
width	1	3/4	½	1/4
m	Ground pressure, kPa			
0.600	335	305	273	238
0.700	304	278	250	220

For the Finnish peatlands, see the literature survey on site bearing capacity in Appendix 4.

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[1] Modelling of the wheel and soil. 1. Tyre and soil contact

Table 4.2 Soil bearing capacity after different authors

Source	1)	2)	Risk		
Soil description	Bearing capacity, kPa				
Moraine, dry	400 - 800		no		
Moraine, moist, fine	200 - 500		some		
Moraine, moist, granular	300 - 600		no		
Gravel, fine		500	no		
Gravel, dry	300 - 700	200 – 600	no		
Gravel, moist	400 - 800		no		
Sand, dry	150 - 250	200	exist		
Sand, moist	300 - 500	400	no		
Clay, dry	400 - 1200	400	no		
Clay, moist	200 - 300	200	exist		
Clay, wet	50 - 150	100	no go		
Alluvial soils		50	no go		
Peatland, wooded	40 - 70		no go		
Peatland, open	10 - 40	20	no go		
Snow, virgin	10 - 30				
Snow, old, -10 C	50 - 100				
Snow, compressed, -10 C	200 - 500				
Snow, hard packed, -10 C	400 - 800	900	no		
Ice	1000 - 2000				

1) Hyvärinen & Ahokas (1975) 2) Ragot (1976)

5. SOIL COMPACTION

5.1 Assessing the soil compaction

The changes in soil compaction degree can be evaluated using different variables. The most common are

- soil dry density, (γ), kg/m³
- soil penetration resistance, (q), kPa
- soil porosity
    - soil porosity, (n_0), %

$$n_0 = 100 \cdot \left(1 - \frac{\gamma_d}{\gamma_s}\right) \tag{5.1}$$

where

n_0	soil porosity, % (where 0 designs original porosity, 1…n pass number)
γ_d	soil dry density, kg/m³
γs	soil solids density, kg/m³

- soil pore index, (e_0), %

$$e_0 = \frac{n_0}{100 - n_0} \quad (5.2)$$

5.2 Soil compaction models

5.2.1 Soil dry density

Soil dry density can be assessed by different methods

- direct methods
  - gravimetric, by taking a sample with known volume, and weighing it when dried. Rather resource intensive, but have the advantage of moisture and density measurement at a time. Reliable, if thoroughly done
- indirect methods
  - tables and other empirical data based on estimated compaction degree and soil type. Need some experience, and give only rough estimates
  - penetrometer profile. A rapid method, but results may differ largely at absolute level between sites, because soil density is only one factor affecting the penetration resistance. Calibration improves the results.
  - gamma radiation probe. Needs qualified personnel and other resources. Calibration also needed.

5.2.2 Soil porosity

Soil porosity model as a function of load factor (N·p), based on 2700 kg/m³ soil solids density , is as follows (based on Löffler 1979):

$$n = 59.5 - 3.27 \cdot \ln(N \cdot p) + 0.55 \cdot (MC - 14)^2 \quad (5.3)$$

where

n	porosity, %
N	number of passes
p	ground contact pressure, kPa
MC	moisture content, %

The application of the model reveals, that there is a certain critical moisture content (= optimum moisture content in road construction terms, when compacting soil layers) 14%. This optimum moisture content depends on soil type, however. Soil compaction is widely used in road construction, and more soil compaction process and soil compaction energy models can also be found in road engineering.

5.2.3 Soil density after vehicle pass

Schwanghart studied the compaction effects of agriculture tractor tyres, which generally have lower tyre inflation pressure than forwarder tyres. He concluded that the soil contact pressure follows the model (Eq 5.4), See Appendix Report No 5.

$$p = 45 + 0.32 \cdot p_i \qquad (5.4)$$

p contact pressure, kPa

p_i tyre inflation pressure, kPa

The soil density after the tyre sinkage is

$$BD = \frac{3.275}{1.86 + \frac{0.31}{0.01 \cdot p + 0.277}} \cdot 1000 \qquad (5.5)$$

where

BD is bulk density, kg/m³

p tyre contact pressure, kPa

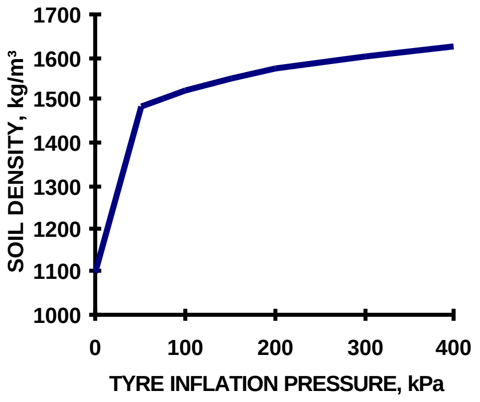

Figure 5.1 Effect of tyre inflation pressure on soil density.

The application of the models (5.4) and (5.5) is visualised in Figure 5.1. It seems, that changes in tyre inflation pressure have minor effect on soil compaction.

5.3 Influence of soil compaction to root growth

In many countries soil compaction in agriculture due to heavier machines and wider tyres is a real problem, and there are several studies on influence of soil compaction to the productivity. Practically in every study a certain decrease in the productivity has been found as a function of soil compaction. There are also several studies in forestry showing negative influence of soil compaction on root growth of trees, or on total productivity. As an example Figure 5.1, where the results of two studies are depicted. It can be seen, that soil penetration resistance should be under 1000 kPa

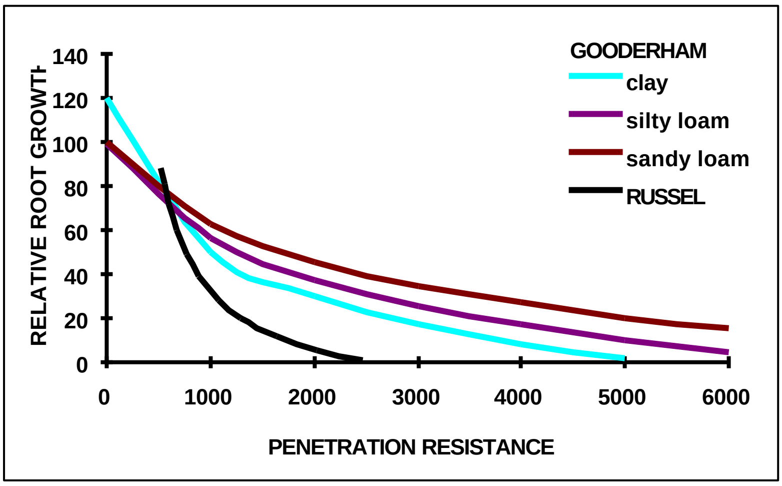

Figure 5.2 Relative root growth a function of soil penetration resistance (After Gooderham 19xx (clay-sandy loam) and Russel (1977)

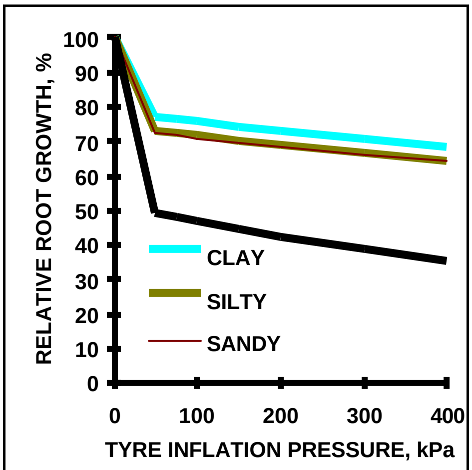

Figure 5.3 Relative root growth after wheel passes with different tyre inflation pressure

A relative value before and after the compaction can be estimated using the following model, Eq(5.6), based on Russel's (1977) data.

$$R\% = \frac{8856}{(q-200)^{0.754}} - 25 \qquad (5.6)$$

where

R% is relative root growth, %
q soil penetration resistance, kPa

The effect of tyre inflation pressure on root growth is visualised in Figure 5.3. Changes in soil density are as depicted in Figure 5.1. (Chapter 5.2.3)

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Appendix 1. NSR Soil Classification

Appendix 2. USCS Soil Classification

Appendix 3. Comparison of the soil penetration models with the field data

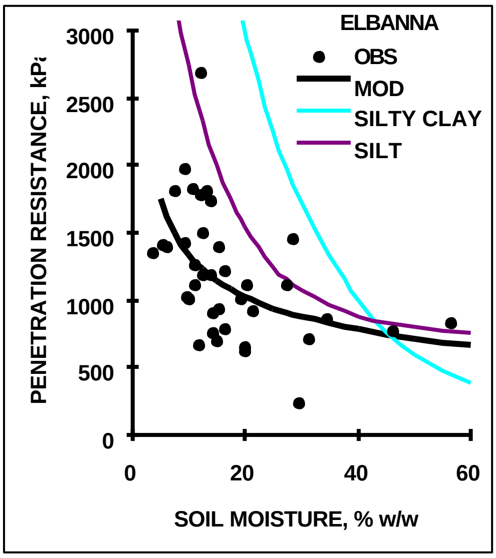

Figure 1. Elbanna & al

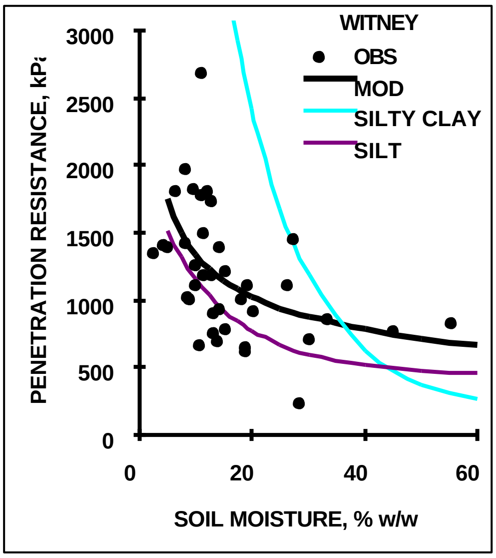

Figure 2. Witney et al

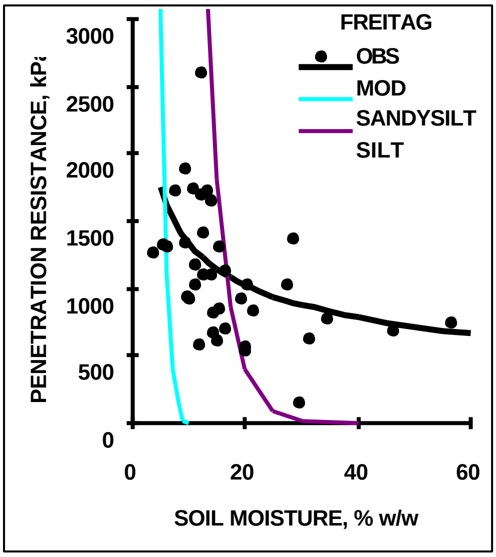

Figure 3 Freitag

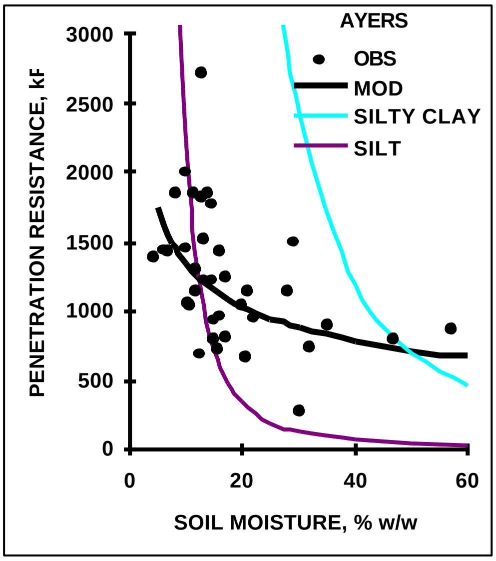

Figure 4 Ayers

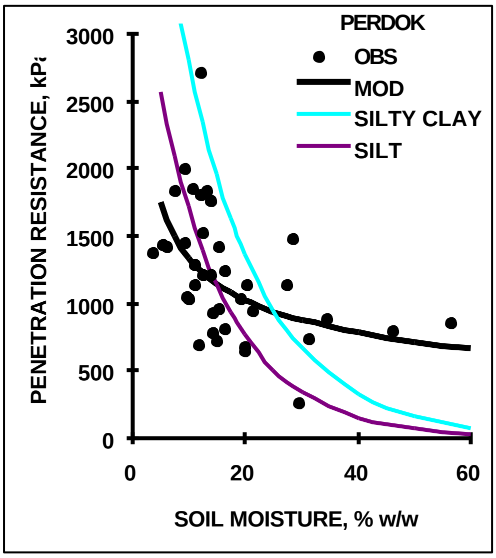

Figure 5. Perdok

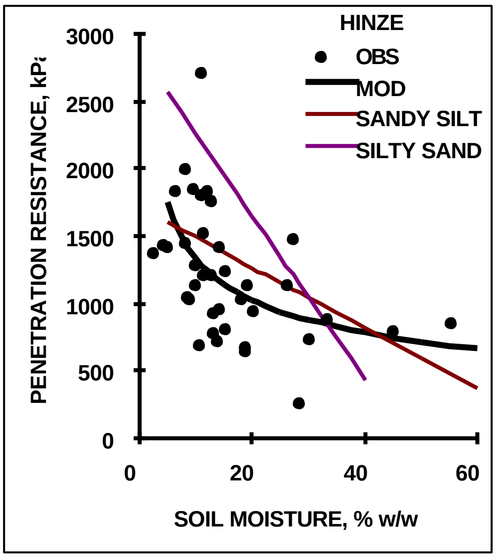

Figure 6. Hinze

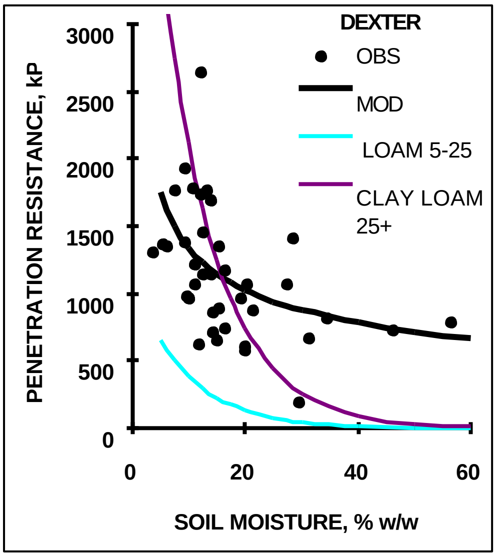

Figure 7. Dexter et al (1988)

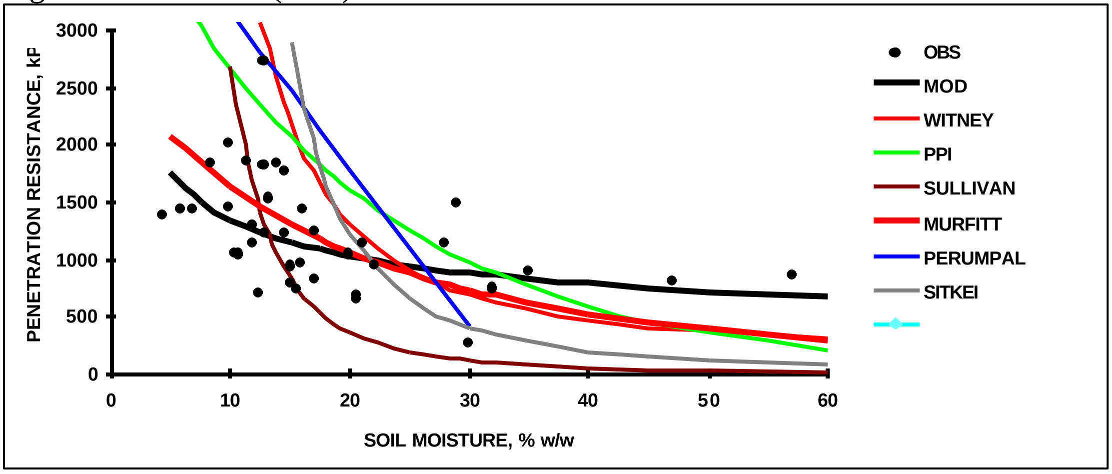

Figure 8 Penetration resistance as a function of soil moisture by different one entry models compared to observations.

Appendix 4. Bearing capacity of Finnish peatlands

Table A4.1 Permitted ground pressure of on different peatland site types after Huikari *et al* (1963) and Saarilahti (1982)

Author	Huikari *et al* 1963			Saarilahti 1982		
Site subtype	Main site type			Main site type		
	Fen	Spruce swamp	Pine swamp	Fen	Spruce swamp	Pine swamp
	Permitted ground pressure, kN/m²					
Rich fen	15	15	20			
Herb rich	30	30	30			
Sedge	30	40	40			
Myrtillus		30			40	
Vaccinium		30				
Carex glubulus		40	40	24-26		26
Small sedge	25	30	30	22		
Eriophorum	25	30	30			30
Sphagnum	15		15	31		24
Rimpi bog	5		5	18		