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Development in techniques for studying forest roads on peatlands

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SELOSTE: SUOTEIDEN TUTKIMUSMENETELMIEN KEHITTÄMINEN

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A light seismic method, a short-pulse radar and a microwave probe are tested in assessing the properties of a forest road constructed on peatland. The light seismic method gave reliable values for estimating the bearing capacity of the road. It was found that bearing capacity was mostly dependent on embankment thickness, but quality of fabric might also have an influence. Embankment thickness and peat depth can be measured on the radargram, and some additional information on road bed and peat obtained. The microwave peat probe permits recording of the continuous moisture profile in situ, which improves accuracy of planning.

Artikkelissa tarkastellaan kevyen seismisen menetelmän, maaperätutkan ja suosondin käyttöä suolle rakennetun metsätien laadun tutkimisessa. Kevyt seisminen menetelmä soveltuu tien kantavuuden mittaukseen. Kantavuuteen voimakkaimmin vaikuttava tekijä oli pengerpaksuus, mutta myös käytetyn suodatinkankaan laatu saattoi vaikuttaa kantavuuteen. Maaperätutkalla voidaan seurata penkereen ja turvekerroksen paksuutta joko videomonitorista tai intensiteettipiirturitulostuksesta. Suosondilla voidaan mitata turvekerroksen kosteusprofiili in situ, ja mitattua kosteutta käyttää hyväksi kehitettäessä entistä tarkempia painumamalleja.

Keywords: subsurface profiling, bearing capacity, moisture content, microwave, fabric, settlement, peat
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1. Introduction

The need for improving forest road planning and construction techniques on peatland is evident because of an intensive forest drainage program in Finland. Studies concerning forest road construction techniques were therefore included in the Inter-Nordic research project "Logging on Peatland". During the earlier stages of the project it was,

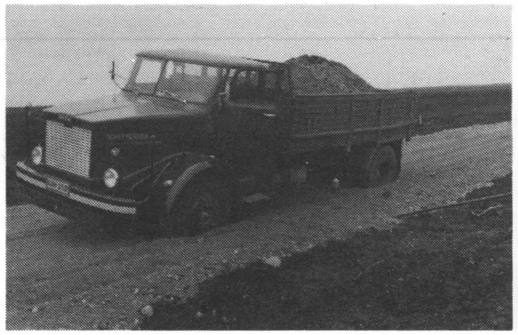


Fig. 1. Technical problem with heavy counterweight on a road with low bearing capacity.

Kuva 1. Levykuormituskoe edellyttää raskasta vastapainoa jonka liikkuminen heikosti kantavalla suotiellä on vaikeaa.

however, discovered that new, more appropriate research methods were needed for measuring the bearing capacity of the road and for evaluating the quality of the construction (Saarilahti 1977). Also the evaluation of peatland properties, mainly measuring of water content, should be simplified before more exact settlement calculations are to be used in forestry.

The plate bearing test generally used in civil engineering is not quite appropriate because:

- the bearing capacity of some sectors is so low that the lorries used as counterweight cause ruptures and are even bogged down, Fig. 1 (Technical problem)
- a heavy lorry is too expensive a counterweight because of long distances between small worksites (Economic problem).

Through the bearing capacity evaluation, another problem was encountered, i.e. the evaluation of fill height. Knowing this is important for studying the subsoil failure and/or the amount of hauled material. Mechanical soundings, e.g. weight sounding, are resource-intensive and give spot-wise information. A continuous profiling of fill height would increase the accuracy of analysis when comparing different construction techniques.

In addition to the problems in evaluating the quality of road bed, another major problem in planning of roads on peatland is the calculation of settlement. Because of good correlation between water content and compressibility of peat knowing the degree of moisture is of first importance.

This paper deals with testing of:

- a light seismic method for measuring bearing capacity,
- a short-pulse radar for continuous profiling of road embankment constructed on the peat layer
- a microwave peat-probe for measuring the water content of peat in situ.

The application of a settlement model (Saarilahti 1980) is also discussed.

The radar equipment has been improved, and the microwave peat sensor has been constructed by the Radio Laboratory of Helsinki University of Technology. Ilkka Marttila, M. Sc. (Eng), assisted in radar soundings; Martti Toikka , M. Sc. (Eng), in microwave probe sounding; Reino Pulkki, L. Sc. (For), in bearing capacity measurements; and Arto Rummukainen, M. Sc. (For), in peat analysis. Jouko Hämäläinen (Civil Eng.) has for several years recorded the settlement. The test road has been constructed by the District of Kuopio, Central Forestry Board, Tapio. The language checking is made by Carol Norris (Ph. D).

2. Presentation of measuring methods

21. Principle of electromagnetic subsurface profiling

The principle of electromagnetic subsurface investigation is presented in Fig. 2; (Morey 1974, Ulriksen 1982). A short electromagnetic pulse is radiated into the earth where it spreads conically at a velocity proportional to the dielectric properties of the medium. The wave is partially reflected back by the interfaces between two mediums with different dielectric properties. The reflected wave generates a weak signal onto the antenna, and can be monitored by the oscilloscope. The thickness of the layer can be calculated based on the known dielectric constants of the medium, eq. (1).

$$h = \frac{c}{2 \cdot \sqrt{\varepsilon_r}} \cdot t \qquad (1)$$

here

h is layer thickness, m

c velocity of the electromagnetic radiation in vacuum, speed of light, 0.2998 m/ns

ε_r relative dielectric constant of the medium

t travel time of the pulse, ns

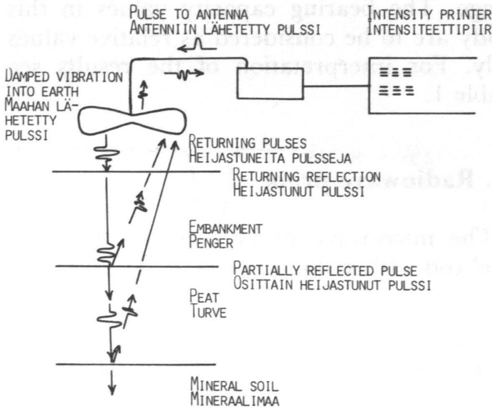


Fig. 2. The principle of radar sounding.

Kuva 2. Tutkaluotauksen periaate.

The theoretical functioning of the radar is complex, and in addition to this its practical functioning has some extra features. Instead of a single pulse the antenna reflects a damping vibration into the earth, which causes the reflecting interface to be presented by 3 to 4 black parallel lines on the radargram.

In this study a commercial radar from Geophysical Survey Systems Inc. has been used, the basic unit fitted with a video monitor.

22. Light seismic method for bearing capacity measurement

The seismic method is a derivation of a so-called light fall-weight deflectometer method (LWF) (see Tholen 1980). The apparatus consists of a ∅ 300 mm loading plate with a perpendicular guide rod. The mass of 14 kg is dropped on the loading plate, and the road surface vibration is registered by two nearby geophones, see Fig. 3. As a rule the shear wave becomes larger as the bearing capacity of the soil decreases (Mooney 1973). Bearing capacity was determined based on an empiric equation developed by Pulkki (1982). His data were collected on roads with good bearing capacity, the Modulus of Elasticity being between 5 and 100 MN/m^2. The bearing capacity of the roads in this study was lower and extrapolation gave negative E-moduli in some cases. It is thus evident that the slope of the fitting curve is too large for the lower

Fig. 3. Light seismic bearing capacity measurement system.

Kuva 3. Kevyt seisminen kantavuuden mittausmenetelmä.

range. The bearing capacity values in this study are to be considered as relative values only. For interpretation of the results see Table 1.

23. Radiowave probe

The microwave probe consists of a thin steel rod with a slot antenna at the end. The antenna creates an electromagnetic field in the medium; the resonance frequency is related to the water content, and the losses to the water content and the conductivity of peat. The conductivity depends on some peat properties, such as decomposition degree and ash content (Tiuri and Toikka 1982, Tolonen et al. 1982). The simplified measuring principle is described in Fig. 4.

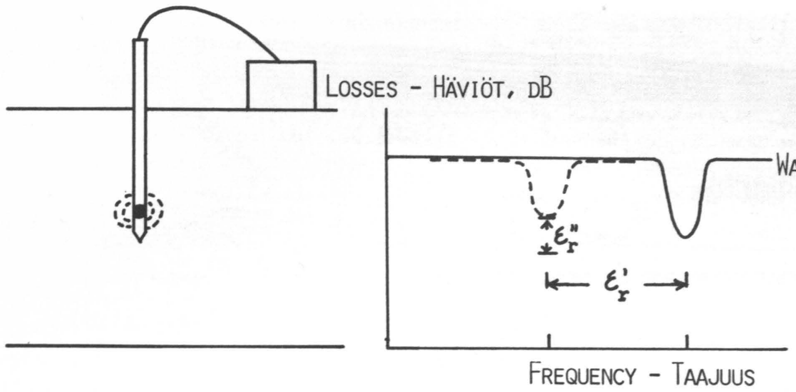
Table 1. Modulus of elasticity in different trafficability classes of forest roads after Pulkki (1982).
Taulukko1. Kimmomoduuli metsätien liikennöitävyysluokittain (Pulkki 1982).

E-modulus *Kimmo-moduuli MN/m²*	Trafficability *Liikennöitävyys*
< 2	Failure, all traffic should be restricted Murtuu, liikennettä ei sallita
3 . . . 10	Only light vehicles should be allowed Ainoastaan kevyt liikenne sallittu
11 . . . 20	Light vehicles and only 1 to 2 heavy vehicles to be allowed, preferably all heavy vehicles should be restricted Sallitaan kevyt liikenne ja 1 . . . 2 raskasta ajoneuvoa, ajoneuvokieltoa raskaille ajoneuvoille suositellaan
21 . . . 30	Reduced heavy traffic volume allowable: maximum of 2 to 3 heavy vehicles per day at low traffic speeds, less than 10 km/h Rajoitettu raskas liikenne sallitaan, korkeintaan 2 . . . 3 raskasta ajoneuvoa päivässä korkeimman sallitun ajonopeuden ollessa 10 km/h
31 . . . 40	Moderate traffic volumes allowable: Heavy vehicles should be restricted to a maximum of 5 per day, and the traffic speed should be less than 20 km/h Kohtuullinen liikennekuorma sallitaan. Raskaita ajoneuvoja sallitaan korkeintaan 5 päivässä korkeimman ajonopeuden ollessa 20 km/h
41 . . . 60	No real restrictions on traffic volume except that vehicles travel at reduced speed (less than 30 km/h) Liikennemäärää ei rajoitettu, mutta korkein sallittu nopeus on 30 km/h
61 >	No traffic restrictions Ei liikennöintirajoituksia

3. Data collection

Two sections of a forest road built on peat were studied. The length of the 1st section is 400 m and the 2nd 380 m. These sections do not represent a normal forest road because of too low a bearing capacity, the second section in particular being so weak that even passenger car traffic meets difficulties. The sections were selected because they were involved in earlier studies dealing with the use of fabrics in forest road construction, and their construction history is well recorded.

The road was built in 1977. Three different types of fabrics were used for strengthening the surface. In the first year an embankment of 0.3 to 0.4 m was hauled onto the frozen road bed. During the next year the embankment of the first section was heightened by hauling additional material. The embankment material varies between sandy moraine and silty sand moraine.



$$\varepsilon_r' = f(u) \qquad \varepsilon_r'' = f(H, a, c)$$

Fig. 4. Principle of radiowave probe.
Kuva 4. Radioaaltosondin mittausperiaate.

The surfaces of the road and peatland were levelled several times between 1977 and 1981 for calculating the settlement. Weight sounding of the road line was carried out in 1977 at 20 m stations. The shear strength of the peat was determined using a vane test in 1979 at the roadside, 20 m off the center-line. The peat analysis and water content measurements were made 20 m off the road center-line in October, 1981. Bearing capacity measurements using the light seismic method were carried out in July and October, 1981, in the middle of the wheel track. The measurements were made at every 5 m on the first and 10 m on the second section. No difference in the results was found between those two dates. The fill height (= embankment height, consisting of the height of all the road structural layers of mineral soil) was measured on the road center-line every 20 m by digging a hole through the embankment. The radar profiling was carried out in October, 1981. The antenna was towed on the road center-line at a distance of 20 m behind a car, but the antenna was occasionally swinging off the center-line.

4. Results

41. Analysis of the radargram

Embankment thickness

Several reflections can be seen on the radargram, (Fig. 5). The grey zone (1) under the antenna noise (0) was interpreted to be influenced by the the reflections from the road bed. The weaker discontinuous intermediate reflections (2) were interpreted to come from interfaces between peat layers and/or to be double reflections from the embankment. The deeper clear reflection was interpreted to come from the peat/mineral

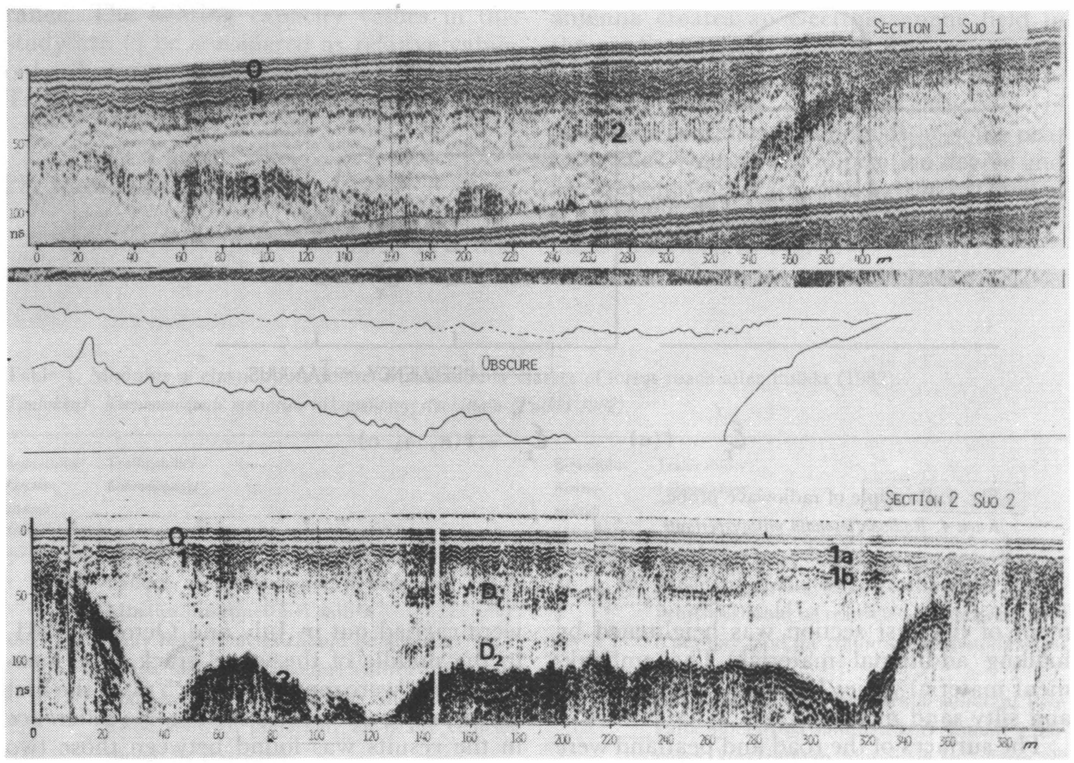


Fig. 5. Radargrams with their interpretation.
Kuva 5. Tutkagrammi tulkintoineen.

soil interface (Saarilahti and Rummukainen 1981, Rummukainen 1982).

For further analysis a continuous line was drawn along the bottom of the grey zone A. Only occasionally was the interpretation uncertain because of the missing of darker reflection. These sections are classified as "obscure reflection". Because the recording of the 1st Section contains a systematic error in counting the time frequency, the radargram seems to taper towards the end. This error was corrected, however, in calculating the travel time.

Using the measured travel time and the relative dielectric constant, $\varepsilon_r = 25$, the corresponding embankment height was calculated. The results are compared with mechanically measured embankment height in Fig. 6. A good fit can as a rule be seen. The only remarkable disagreement is found at the station 340 where the calculated embankment was 0.64 m and the measured one 0.92 m. This might be due to

- variation in ε_r-values
- two types of locality error
  - human error: the event marker button being pushed incorrectly or an error in recording the measurement
  - technical error: the antenna having moved off the road center-line. As the bottom of the road is convex, the error may become noticeable
- error in interpretation of the radargram, because of "obscure reflection".

The most probable reason is technical locality error: the antenna has moved off the center-line. An obscure reflection indicates a weak mineral soil/peat interface which might be caused by large differences in embankment thickness.

As for measuring the embankment thickness by radar it can be concluded that

- **good relative embankment thickness can be obtained: the correlation coefficient between the pulse travel time and measured embankment thickness was r = 0.84***, N = 62.**
- **if further information is available (several points studied by mechanical sounding, or ε_r-value known or able to be estimated) true embankment height can be calculated.**

Peat layer thickness

On the radargram the bottom reflection was clear and easy to interpret (Fig. 5). The travel time exceeds the scale on the first section, but it was visible when a larger scale was used. The radar measured peatland depth was calculated using eq. (2).

$$h_o = \left(t - \frac{2 \cdot \sqrt{\varepsilon_{rh1}}}{0.2998} \cdot h_1\right) \cdot \frac{0.2998}{2 \cdot \sqrt{\varepsilon_{rh2}}} + \Delta h \qquad (2)$$

where

h_0 is	initial peatland thickness, m
t	bottom reflection time, ns
ε_{h1}	dielectric constant of the embankment, ($\varepsilon_r = 25$)
ε_{h2}	dielectric constant of the (compressed) peat, ($\varepsilon_r = 64$)
h_1	measured thickness of the embankment, m
Δh	difference between the initial peatland surface level and the current road center-line level, m

In Fig. 7 the radar sounding profile is compared with weight sounding. A rather good fit is evident, although there is some discrepancy at stations 200 to 350. One part

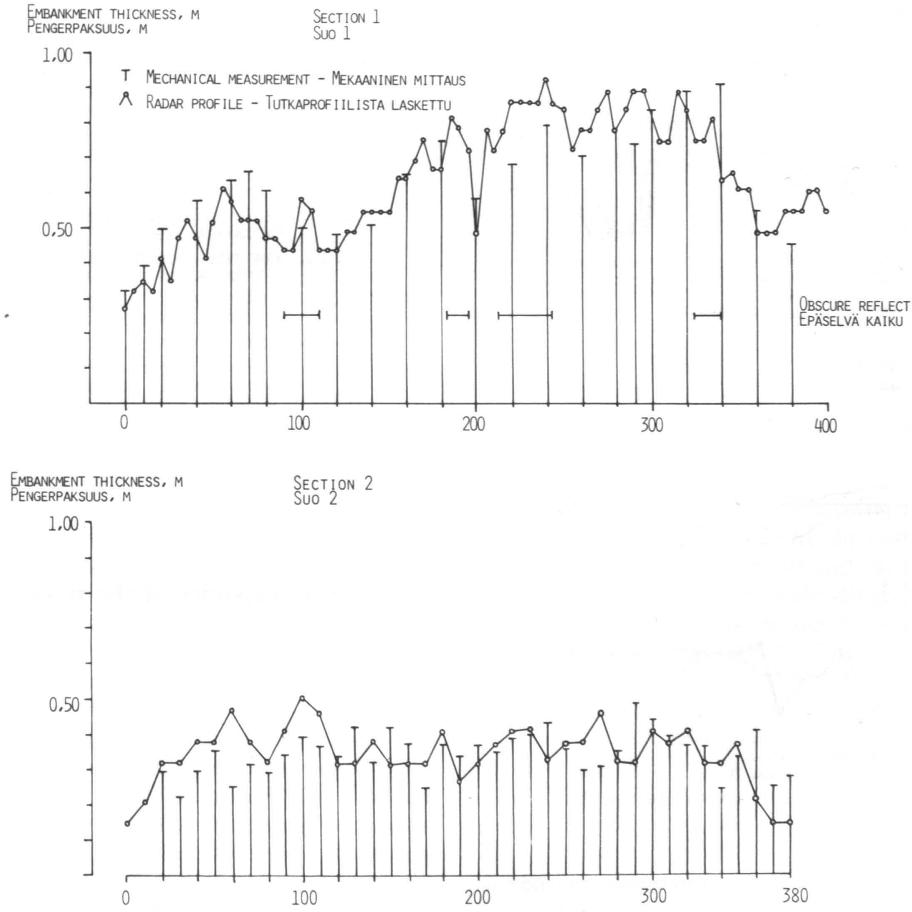


Fig. 6. Mechanically measured embankment height compared with radar sounding.
Kuva 6. Mekaanisella ja tutkamittauksella saadun pengerpaksuuden vertailu.

of the discrepancy might originate from the locality error, another part from the interpretation of peat layer/other soft layers. It is true that the bottom depth profile differs greatly between different measurements (Fig. 8) and the mechanical sounding also shows some inaccuracy. It is possible to monitor the peat bottom through the embankment, a method required when analysing settlement.

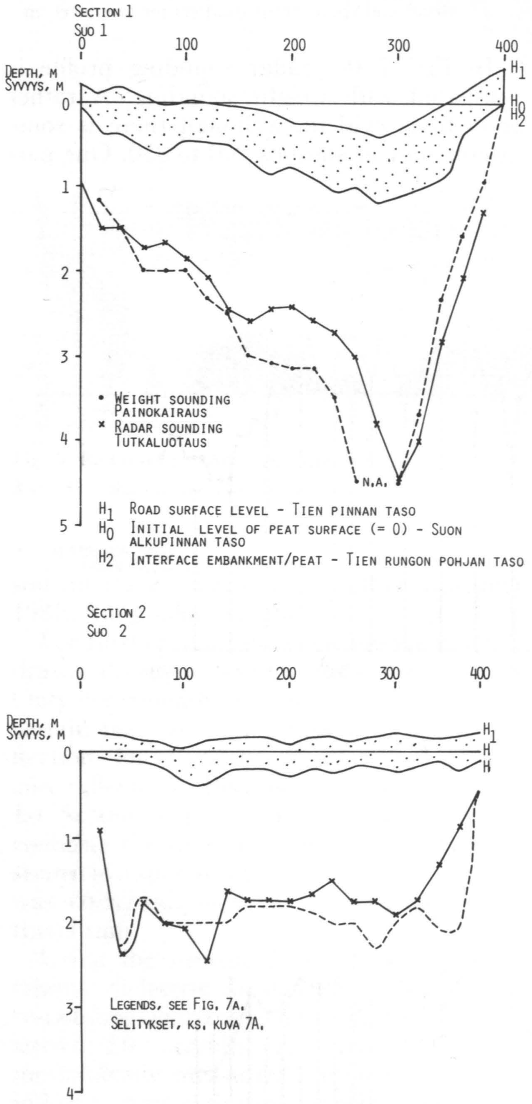


Fig. 7. Peatland bottom profile by mechanical and radar soundings.

Kuva 7. Suon pohjaprofiili mekaanisesti mitattuna ja tutkagrammista tulkittuna.

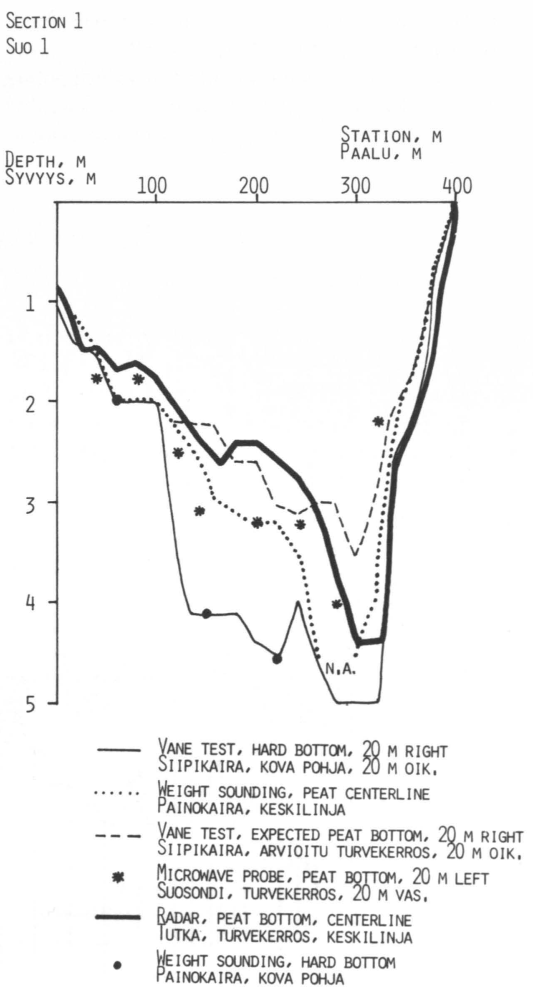


Fig. 8. Peat depth by different soundings.

Kuva 8. Suon pohjan syvyys eri menetelmillä mitattuna.

42. Bearing capacity of the road

The measured Modulus of Elasticity varied between −18 and 68 MN/m^2 on the first section and −20 to 32 MN/m^2 on the second. The negative values are impossible but are due to extrapolation outside the range of Pulkki's (1982) original data. The true bearing capacity range for these negative values is about 100 to 1000 kN/m^2. The measured bearing capacity profile is presented in Fig. 9. It was found that bearing capacity was highly dependent on embankment thickness, the best models being:

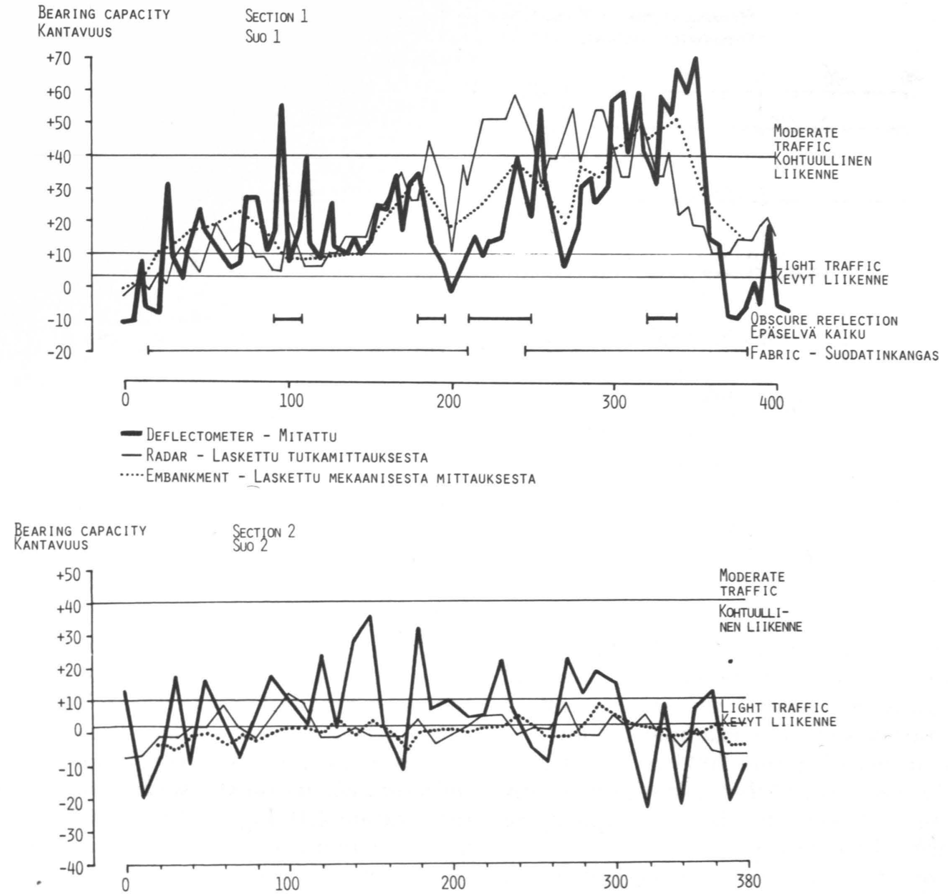


Fig. 9. Measured and calculated bearing capacity.

Kuva 9. Mitattu ja laskettu tien kantavuus.

Section 1 $E = -19.9 + 91.8 \cdot h^2 \quad r = 0.904 \quad N = 25$ (3)

Section 2 $E = -14.4 + 141.5 \cdot h^2 \quad r = 0.447 \quad N = 37$ (4)

All data $E = -8.9 + 73.7 \cdot h^2 \quad r = 0.736 \quad N = 62$ (5)

where

E is Modulus of Elasticity, MN/m^2

h embankment height, m

Theoretically, the quality of subgrade has an influence on the bearing capacity of the embankment, (see for example Lehtinen 1965). In this study embankment thickness was correlated with peat depth and vane shear strength, and their influence cannot be discerned.

The measured bearing capacity profile is compared with the calculated one in Fig 9. Calculated bearing capacity is obtained by using measured embankment thickness and radar measured embankment and the equations (3) and (4). A noticeable disagreement between radar and deflectometer results can be found at stations 200 to 300, section 1. This is due to:

- overestimated radar measured embankment thickness and
- less than average bearing capacity along this part.

Another difference occurs at the stations 340 to 360, where the measured bearing capacity is higher than calculated. One part of the error is evidently due to locality error.

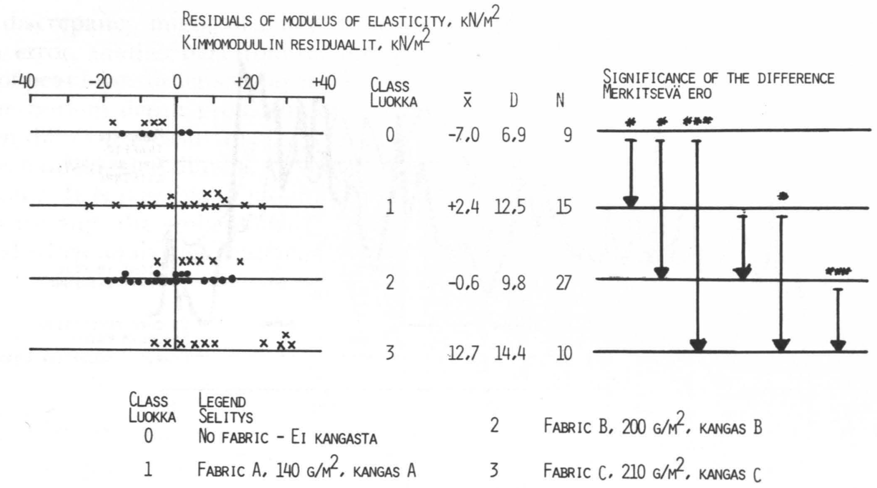


Fig. 10. Influence of fabrics on bearing capacity.
Kuva 10. Suodatinkangaslaatujen vaikutus tien kantavuuteen.

Even though there is some discrepancy in absolute level between the mechanically and radar measured values, the relative values match rather well. For example the low bearing capacity of station 200 can be detected from the radargram. The radargram seems useful in evaluating the bearing capacity of road embankment on peat.

The road was constructed using 3 different types of fabrics:

A: spunbonded, 140 g/m^2
B: needlefelt, 200 g/m^2
C: spunbonded, 210 g/m^2

One 20 m station was without strengthening, and there were also some stations on both ends of the road without fabrics. The influence of fabrics was studied by analysing the residuals of eq. (5). The results are presented in Fig. 10. There is some evidence that the sections without fabric are weaker than the sections with fabric A or B and strong evidence that sectors without fabric are weaker than sectors with fabric C. Sectors with fabric C also have higher bearing capacity than sectors with fabric A or B, but between sectors with fabric A and B no difference appeared. Although the tests showed statistically significant differences between fabrics we have to keep in mind that the layout of the test is not quite representative. For example, most of the 0-sections were situated at the junction of mineral soil/peatland which differs from the inner areas of peatland. Also the influence of a fabric is accentuated due to a thin (non-bearing) embankment. The measuring method also accentuates the difference.

It is noticeable that the largest obscure reflection occurs on the section without fabrics (station 220, Fig. 5). Obviously the interface embankment/peat is not smooth, and some mixing of the material might occur.

43. Measuring the moisture content

The moisture content and the humification of the peat are the main factors when estimating settlement and risks of failure in peat. Even information concerning the humification of the peat is possible when using the microwave probe (Tolonen et al. 1982) only the determination of moisture content is discussed here.

A total of 43 points was studied using the probe, and frequency vs depth recorded. Later the data were analysed at 10 cm depth averages. Core samples were taken from 2 points, and the water content in 10 cm slices was studied using the gravimeter method (Peat testing . . . 1979). A significant correlation between frequency and moisture (Fig. 11) indicates that moisture measurement in

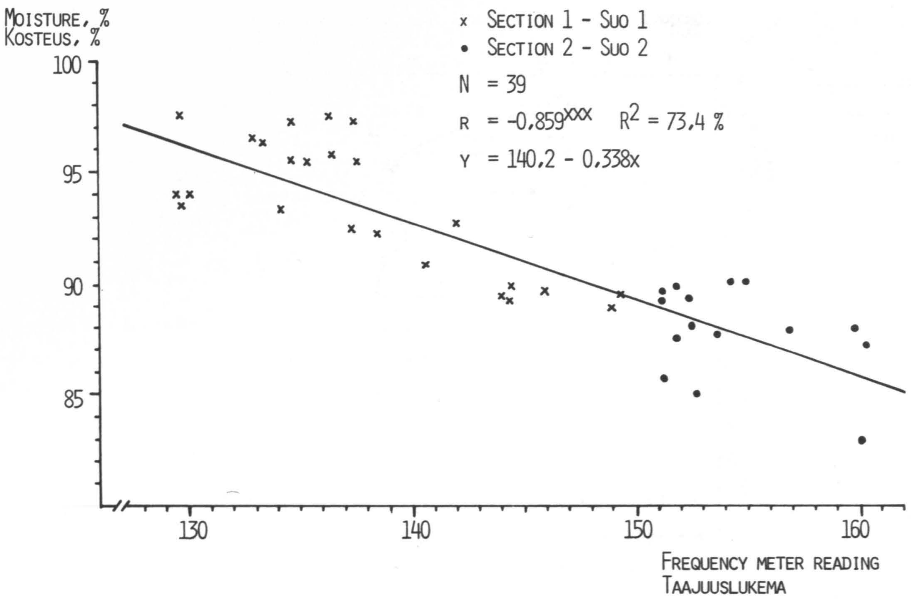


Fig. 11. Correlation between resonance frequency and moisture content.
Kuva 11. Kosteuden ja resonanssitaajuuden välinen riippuvuus.

situ is possible. Using the following empiric equation (6)

$$M = 140.2 - 0.338 \cdot f \qquad r = 0.857 \qquad (6)$$

where
M is moisture content, %
f frequency, MHz

the readings at the other points were converted to moisture and moisture profiles were drawn, (Fig 12). It can be seen that the two peatlands differ from each other. The surface of section 1 is dry (moisture 91 to 94 %), and moisture increases towards the bottom (94 to 95 %). Humification follows the same trend. This pattern is the most common one in Finnish peatlands (Mäkilä 1980). The second section has a wet (95 %) raw peat at the surface and a drier (92 %), well humified mid-layer. There is a third layer, somewhat less humified and wetter (93 %), at the bottom. Both the interfaces can be seen in the radargram, (D1 and D2 in Fig. 5).

44. Dielectric constants

The mode value $\varepsilon_r = 21$ was obtained for the embankment material. This corresponds to very wet sandy loam (Davies et al. 1977). The dielectric constant of the compressed peat under the embankment seemed to be between 65 and 66. As the measured moisture varied from 88.4 to 90.1 %, and the corresponding calculated value using the equation of Tiuri and Toikka (1982) $\varepsilon_r = 64.2 - 65.5$, the figures seem to match.

45. Testing of settlement model

The settlement model (Saarilahti 1980), eq. (7), was tested using three different input variables:

$$S = Q \cdot h_o^{0.85} \cdot m_t \qquad (7)$$

where
S is settlement, m
Q load due to embankment, kN/m^2
ho initial peat layer thickness, m
m_t settlement factor

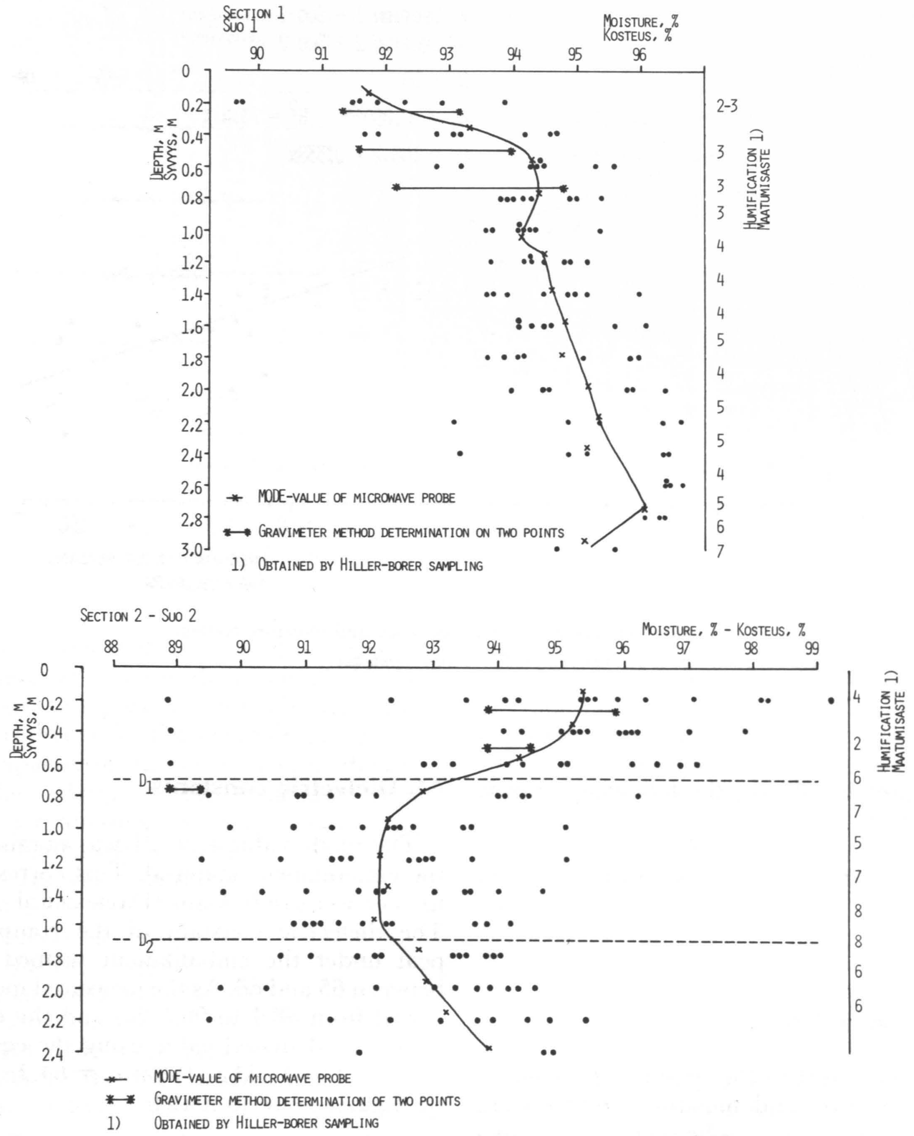


Fig. 12. Moisture profiles of the peatlands.
Kuva 12. Soiden kosteusprofiilit.

1) The water content was measured by radiowave probe and the settlement factor calculated using eq. (8)

$$m_t = 0.009 + 0.000\,008 \cdot MC \qquad (8)$$

where
m_t is settlement factor
MC moisture content, %

2) The peat shear strength was measured by the vane test and the settlement factor calculated using eq. (9)

$$m_t = e^{3.3 - 0.06 \cdot \tau} \qquad (9)$$

where
m_t is settlement factor
τ peat shear strength, kN/m^2

Table 2. Comparison of the three methods in estimating the settlement.
Taulukko 2. Painumalaskelmamenetelmien vertailu.

Method *Menetelmä*	Nb. of Obs. *Havaintoja*	Correlation coefficient *Korrelaatiokerroin*	Equation *Yhtälö*	Absolute error *Absoluutinen virhe, m*
1 eq. (8)	37	0.928	Y = 0.03 + 0.91 · X	+ 0.23 . . . −0.46
2 eq. (9)	37	0.918	Y = 0.05 + 1.25 · X	+0.46 . . . −0.06
3 fixed kiinteä m_t	37	0.952	Y = −0.05 + 1.09 · X	+ 0.18 . . . −0.09

3) Using the fixed m_t -value of 0.023 for "Neva" (fen) — type. This corresponds to the moisture content of 1 750 equal to 94.5 % moisture.

Regression analysis gave the results found in Table 2. The best estimates were obtained by using fixed moisture content; because eq. (8) has been developed from material in which the moisture was the average of 1 to 2 samples taken from 0.25, 0.50 and 0.75 m depths, and the very low moisture measured at one point (Station 300, see Fig. 13) gave too high an estimated settlement. Method 2, using measured vane strength, has one possible source of difference: the peat layer depth used in calculations was measured by weight sounding instead of being based on the vane depth as in development of the equation (9).

Even though the settlement estimates are still acceptable for practical applications, the conclusion is that the new improved peat investigation method, using the microwave probe necessitates the development of better settlement calculation methods, for example, new improved models for evaluating the settlement factor.

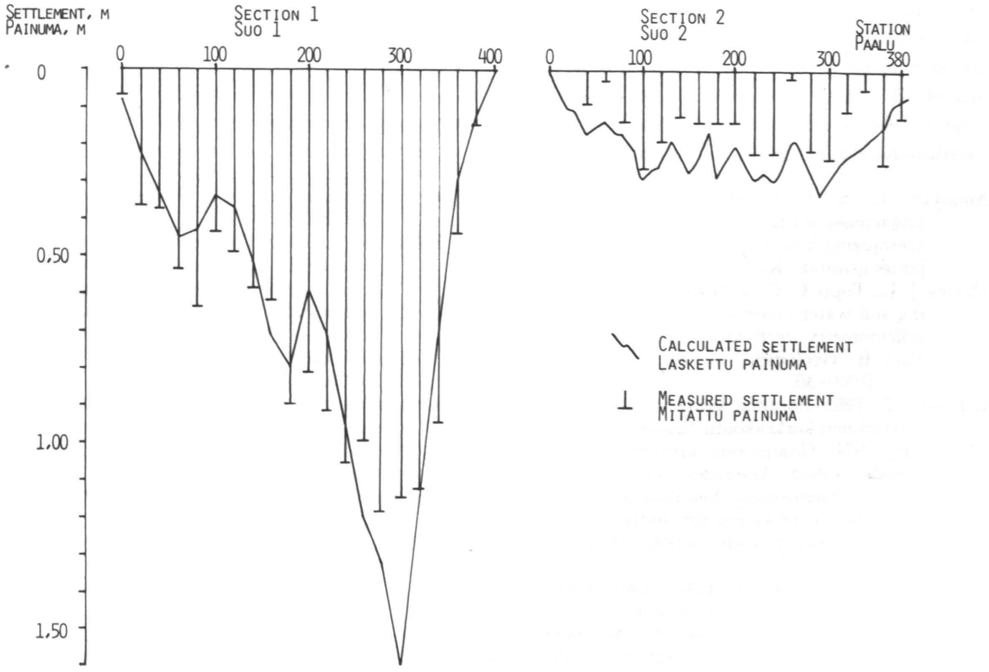


Fig. 13. Actual settlement compared to the calculated (eq. 8).
Kuva 13. Mitatun ja mallilla (8) lasketun painuman vertailu.

5. Practical applications

The methods tested have different possible applications. Radar sounding can be used either for planning or for studying roads. If long routes with several alternatives are to be compared, the preliminary investigation of the peatland is possible by using radar sounding, because essential information as to

- peat layer
- depth
- homogeneity
- adjacent mineral soil
- soil type (moraine, sand, clay or mud)
- boulders

can be seen in the radargram (Saarilahti 1982a). Mechanical soundings can then be directed to the problematic parts of the profile. The economics depends on the terrain transport costs of the radar unit. On open and smooth peatland radar sounding is easy to manage. Short passages on woody peatlands, however, become relative costly, so radar sounding seems rather an expensive tool for today's planning. In studying the road bed the value of the information increases because its accuracy and low transport costs of radar on road. Therefore the radar is a more appropriate tool for research purposes.

The microwave probe is a promising tool for planning purposes because it provides an accurate spot-wise moisture profile. The compressibility (Tkacenko 1972) and shear strength (Amarjan 1972) of peat are strongly dependent on moisture. As all the essential elements for evaluating the settlement can be collected by one push it seems economically feasible.

The usefulness of the light seismic method is also evident and the bearing capacity survey can be added to research projects without enlarging the budget too much. The bearing capacity survey can also be carried out when planning a repair scheme.

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Seloste

Suoteiden tutkimusmenetelmien kehittäminen

Artikkelissa tarkastellaan kevyen seismisen menetelmän, maaperätutkan ja suosondin käyttöä suolle rakennetun metsätien laadun tutkimisessa sekä testataan pistemäisten kosteusmittausten käyttöä aiemmin keskimääräiseen kosteuteen perustuvassa painumamallissa. Tutkimuskohteena oli yhden metsätien kaksi suo-osuutta yhteiseltä pituudeltaan 780 m. Tietä rakennettaessa kokeiltiin kolmea eri suodatinkangasta pohjanvahvisteena. Kevyt seisminen menetelmä soveltuu tien kantavuuden mittaukseen, ja havaittiin että kantavuuteen voimakkaimmin vaikuttava tekijä oli pengerpaksuus, mutta myös käytetyn suodatinkankaan laatu saattoi vaikuttaa kantavuuteen. Maaperätutkalla voidaan seurata penkereen ja turvekerroksen paksuutta joko videomonitorista tai intensiteettipiirturitulostuksesta ja näin saada informaatiota tien rakenteesta, kantavuudesta ja siihen mahdollisesti vaikuttavista tekijöistä. Suosondilla voidaan mitata turvekerroksen kosteusprofiili in situ. Kuitenkin mikäli tarkempia kosteuden mittaustuloksia aiotaan hyödyntää on kehitettävä entistä tarkempia painumamalleja.