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Measurement of the Acoustic Impedance of Ground

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SP Swedish National Testing and Research Institute
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Abstract

Different ways to determine the acoustic impedance of the ground have been tested. The conclusion is that, at present, the simplest and most efficient method is the level difference method, which uses two microphones and a source to make a propagation measurement. Due to weather effects the geometry has to be small (a few meters), and for very hard surfaces and low frequencies, no information can be obtained. The measured sound pressure level difference between the two microphone positions is compared with calculated values to obtain a best fit. A Nordtest method is proposed. The precalculated values are given for 12 different ground impedance classes using a one or two parameter impedance model. The measurements are carried out in third octave bands within the frequency range 200-2500 Hz. The measurement is qualified by studying the error relative pre-calculated curves and the standard deviation of four measurements at the same test site.

Verification measurements by 4 test teams on 4 different test sites show that the measurement uncertainty is ± one flow resistivity class. In addition to impedance values for these 4 test sites other test results on other ground types are reported.

Key words: acoustic impedance, sound propagation, ground effect, level difference method

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Preface

The initial investigations and some measurements have been funded by KFB, the Swedish Transport and Communications Research Board, project 1997-0222 and the final work with the test method, including its verification, has been funded by Nordtest project 1365-1997.

The Nordtest project was carried out by a project group consisting of Hans Jonasson (project leader) and Mikael Ögren, SP, Jørgen Kragh and Birger Plovsing, Delta Acoustics and Vibration, Svein Storeheier, SINTEF and Juhani Parmanen, VTT. In addition Tomas Ström, SP, and Reijo Heinonen took part in the comparison measurements.

Gilles Daigle of the National Reseach Council of Canada supplied us with the latest proposal for an ANSI standard.

The valuable contributions of the above individuals and institutions are gratefully acknowledged.

Conclusions

- The ground impedance can be measured with the level difference method
- The level difference method must use small geometries, and is not applicable to very hard surfaces
- Using flow resistivity classes makes the evaluation of the measurements very simple for the user, and does not affect the measurement quality if the classes are chosen appropriately
- During the verification measurements it was shown that the method gives stable results within +/- one flow resistivity class
- The accuracy of the method can be improved for snow (or other layered surfaces) by using a two parameter impedance model

1 Introduction

When predicting outdoor noise propagation the ground impedance is an important parameter. Soft surfaces have a relatively low impedance, which leads to a high ground attenuation, and thus lower sound pressure levels. By the year 2001 a new Nordic sound propagation method shall be ready for use, and in order to make good predictions with this new and accurate model we need to have accurate input data for the ground impedance.

This report presents some initial investigations, a proposal for NORDTEST method and some experimental data. The second chapter defines the necessary quantities and describes the theory for sound propagation near the ground. Chapter 3 describes a few impedance models, which describe how the impedance varies with frequency and with one or more parameters. In chapter 4 the different known methods are discussed, and in chapter 5 a few experiments are presented to verify the basic properties of these methods. The more specific decisions and conclusions for the NORDTEST method is discussed in chapter 6, and in 7 a number of measurement results with the aim of verifying the method is presented. Chapter 8 contains a number of measurement results using the measurement method proposed in an annex.

2 Definitions of impedance and how to calculate the ground effect

2.1 Impedance and admittance

The specific acoustic (surface) impedance is defined as the complex ratio of the effective sound pressure at a point of an acoustic medium to the effective particle velocity normal to the surface (positive direction into the surface) at that point. The SI unit is Ns/m^3. The word "specific" implies "per unit area", since pressure is force per unit area.

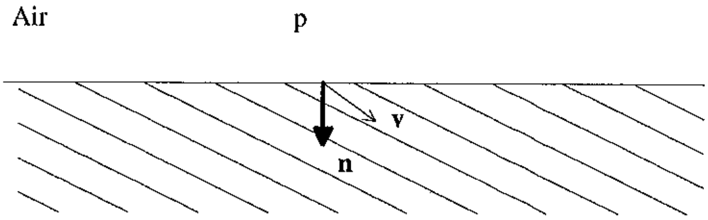


Figure 2.1
Definition of specific acoustic impedance.

$$Z_S(\omega) = \frac{p}{v \bullet \mathbf{n}} \tag{2.1}$$

The admittance is the inverse of the impedance. The real part of the impedance is called resistance and the imaginary reactance. We assume the harmonic time dependence to be described by $e^{-i\omega t}$. In literature where the harmonic time dependence is described as $e^{i\omega t}$, the reactance would have the opposite sign of what the definition here would give. The unit of the impedance is Ns/m^3.

To characterize a ground surface it is usual to state the surface impedance normalized to the impedance of air, $Z=Z_S/\rho_0 c$, where ρ_0 is the density of air, and c the speed of sound. In the following text the normalized specific acoustic impedance is referred to as impedance.

2.2 Local and extended reaction

A surface is called locally reacting if the particle velocity ($\boldsymbol{v \bullet n}$) at a point depends only on the pressure p at the same point. If this is not the case, the surface is called extendedly reacting. The assumption that a surface is locally reacting is the same as to assume that the impedance of the surface is independent of the angle of incidence. There is no evidence, possibly with the exception of loose snow, that suggests that normal ground surfaces can not be classified as locally reacting. In this text local reaction is assumed for all surfaces.

2.3 Plane wave reflection

Assume that we have a plane wave above a semi infinite impedance boundary with angle of incidence θ. Then the reflection coefficient R would be:

$$R(\theta) = \frac{\cos(\theta) - \beta}{\cos(\theta) + \beta} \tag{2.2}$$

β is the normalized admittance (1/Z). Our sound field above the boundary would consist of one incident part, and one reflected part that would be multiplied by *R*. *R* is a complex number, so the reflected wave would be shifted in phase and in amplitude.

2.4 Spherical wave reflection

If our source and receiver are close to the surface, then we will not have plane wavefronts. Then we must use the spherical reflection coefficient *Q* instead of *R*.

$$Q = R(\theta) + [1 - R(\theta)]E(\rho) \tag{2.3}$$

The function *E(ρ)* is

$$E(\rho) = 1 + i\sqrt{\pi}\rho e^{-\rho^2} erfc(-i\rho) \tag{2.4}$$

$$erfc(x) = 1 - erf(x) = \frac{2}{\pi^{1/2}} \int_x^\infty e^{-t^2} dt \tag{2.4b}$$

where the numerical distance ρ is

$$\rho = \frac{1+i}{2} \sqrt{kR_2} (\beta + \cos(\theta)) \tag{2.5}$$

This solution is valid whenever $|\beta|^2 << 1$ and $\theta \cong \frac{\pi}{2}$ and it has been shown to work rather good even if these conditions are violated a little. All the calculations of *E(ρ)* in this text have been made using the series expansions given in [11]. R_2 is defined in figure 2.2.

2.5 Propagation over an impedance boundary

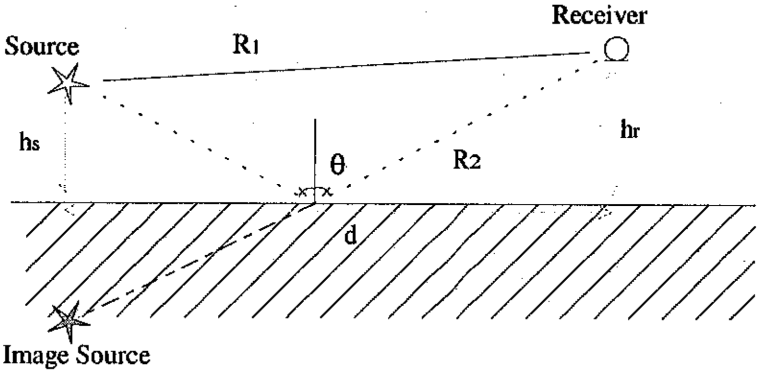


Figure 2.2
Source and receiver above an impedance plane.

The sound field above an impedance boundary with a point source above it can be approximated by (2.6).

$$p = \frac{e^{ikR_1}}{R_1} + Q\frac{e^{ikR_2}}{R_2} \qquad (2.6)$$

The solution is a function of R_1, R_2 (space coord.) and k (wavenumber). The time dependence $e^{-i\omega t}$ is omitted. To get rid of the geometrical spreading, and only study the propagation loss, we normalize with a free, outward-moving wave p_0. This is called the value relative free field,

$$\frac{p}{p_0} = 1 + Q\frac{R_1}{R_2}e^{ik(R_2-R_1)} \qquad (2.7)$$

For frequency band calculations we have to use a smoothing function, see [21], to get the correct values, (2.8). The smoothing factor Δf_r=0.116 for third octave bands. Here $Q=|Q|e^{i\varphi}$.

$$\frac{p}{p_0} = \left(1 + \left[\frac{R_1}{R_2}\right]^2 |Q|^2 + \frac{2R_1}{R_2}|Q|\frac{\sin[k(R_2-R_1)\Delta f_r]}{k(R_2-R_1)\Delta f_r}\cos[k(R_2-R_1)+\varphi]\right)^{1/2} \qquad (2.8)$$

The sound pressure level (SPL) relative to free field is simply p/p_0 expressed in decibels,

$$L_{p0} = 20\log\left|\frac{p}{p_0}\right| \qquad (2.9)$$

2.6 Level difference

The level difference between two different receivers at different heights, but with the same source, is defined in (2.10). Receiver 1 is the receiver closest to the ground surface.

$$\Delta L = L_{p2} - L_{p1} \tag{2.10}$$

For measurements we use some form of L_{eq} values, and for calculations we calculate L_p without free field normalization, but including third octave band smoothing if applicable. The simplest way to do this is to use formula (2.11). Δf_r=0 removes the smoothing.

$$L_p = 10\ \log\left(1+\left[\frac{R_1}{R_2}\right]^2|Q|^2+\frac{2R_1}{R_2}|Q|\frac{\sin[k(R_2-R_1)\Delta f_r]}{k(R_2-R_1)\Delta f_r}\cos[k(R_2-R_1)+\varphi]\right)\ -20\log(R_1) \tag{2.11}$$

To be able to determine which calculated level differences fit the measured data best, we define an error (2.12). This error is the sum of the absolute values of the difference between measured and calculated level difference in a frequency band over all considered frequency bands. ΔL_M is the measured level difference, and ΔL_C is the calculated (using (2.10)).

$$E = \sum_f |\Delta L_M - \Delta L_C| \tag{2.12}$$

Note: The error is defined as the square of the absolute value of the difference in the following figures: 5.2, 5.4, 5.6. This is due to the fact that early in the project we had this definition of the error, but it was later decided to change this into (2.12).

3 Impedance models

3.1 General

The ground effect in sound propagation is determined by the impedance of the ground and of the geometrical situation. The ground behavior is strongly dependent on frequency. If we make a few assumptions of the physical properties of the ground, we can construct a theoretical model of the acoustical behavior in the form of an impedance model. We can also construct an empirical model from measured data. The purpose of an impedance model is to describe how the impedance varies with frequency, and possibly how it depends on other physical parameters, such as porosity.

3.2 One and two-parameter models

A one-parameter model which was first described in [18], uses σ, the effective specific flow resistivity, as a parameter.

$$Z_\infty = 1 + 9{,}08\left(\frac{1000f}{\sigma}\right)^{-0{,}75} + i11{,}9\left(\frac{1000f}{\sigma}\right)^{-0{,}73} \tag{3.1}$$

As a rough guideline, σ should be between 20 000 (soft snow) and 20 000 000 (old asphalt). This model is developed to be good for high frequencies and is not necessarily suitable for low frequencies. Note that σ is just a parameter, but it is usually said to have the same unit (Ns/m^4) as the physical quantity flow resistivity. The one-parameter model can be expanded to a situation where the porous material is backed by a very hard surface, and then we get a two-parameter model and the following formula should be used:

$$Z_L = Z_\infty i \cot(Lk) \tag{3.2}$$

$$k = \frac{2\pi f}{c}\left[1 + 10{,}8\left(\frac{1000f}{\sigma}\right)^{-0{,}70} + i10{,}3\left(\frac{1000f}{\sigma}\right)^{-0{,}59}\right] \tag{3.3}$$

L is the depth of the porous material. (3.3) presumes homogeneous ground. Some examples of impedances according to (3.1) and (3.2) are given in figure 3.1 and 3.2 respectively.

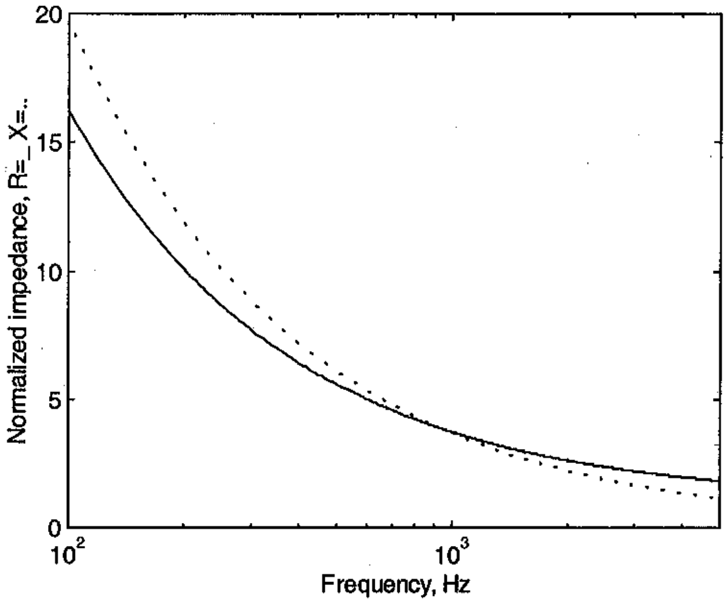


Figure 3.1
Impedance according to (3.1), σ=200 000
— *R*
- - - *X*

Z=R+iX

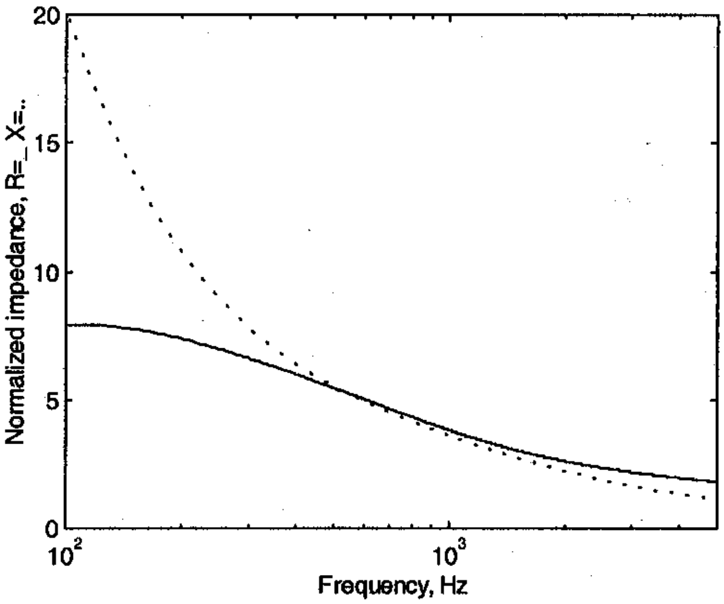


Figure 3.2
Impedance according to (3.2) and (3.3), σ=200 000 and L=0.03m (Hard backing)
— *R*
- - - *X*

Z=R+iX

As can bee seen in figure 3.1 and 3.2, the effect of the hard backing is seen as a decreasing resistivity for low frequencies compared to the infinite layer case. Also note that in figure 3.2 the reactance is greater than the resistance for low frequencies, but for high frequencies it is the other way around.

An alternative one-parameter model is described in [9].

$$Z = 0.218\sqrt{\frac{\sigma}{f}}(1+i) \tag{3.4}$$

In [13] eq. (3.1) is used as the one-parameter model, and as a two-parameter model the following equation is used

$$Z = 0.484(1+i)\sqrt{\frac{\sigma}{f}} + 30i\frac{\alpha_e}{f} \tag{3.5}$$

where α_e represents an effective rate of change of porosity with depth. α_e is in the region of 3 - 250 m^{-1}. In figure 3.3 and 3.4 we can see that the porosity change only affects the reactance, which is also obvious in (3.5).

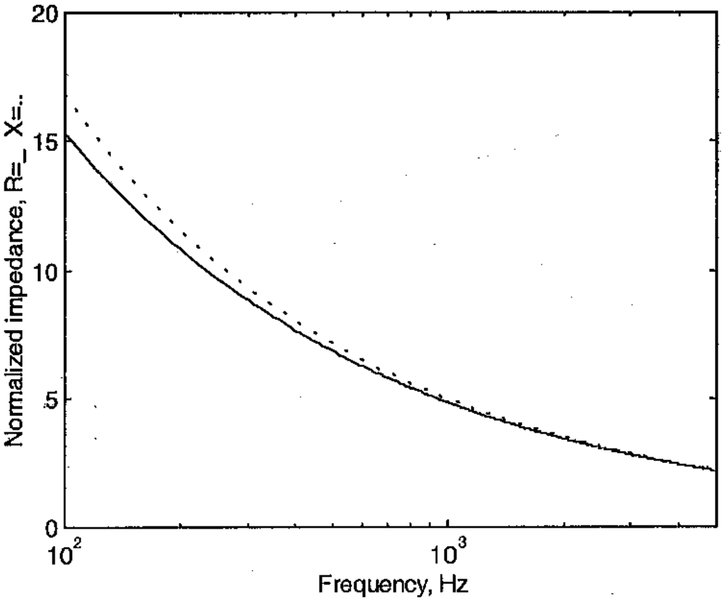


Figure 3.3
Impedance according to (3.5), σ=100 000 and α_e=5 m^{-1}
— R
- - - X

Z=R+iX

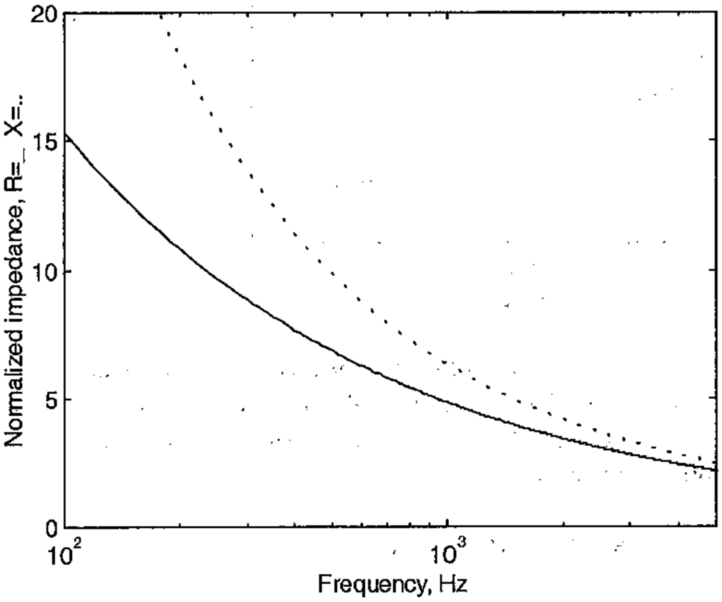


Figure 3.4
Impedance according to (3.5), σ=100 000 and α_e=50 m^{-1}
— R
- - - X

Z=R+iX

3.3 Four parameter models

In [13] there is also a 4-parameter model given by

$$Z = \frac{\rho_b(\omega)}{k_b(\omega)\rho} \tag{3.6}$$

where

$$k_b^2(\omega) = \gamma\Omega\left[\left(\frac{4}{3}-\frac{\gamma-1}{\gamma}N_{pr}\right)\frac{q^2}{\Omega}+\frac{i4s_p^2\sigma}{\omega\rho}\right] \tag{3.7}$$

$$\rho_b(\omega) = \rho\left(\frac{4q^2}{3\Omega}+i\frac{4s_p^2\sigma}{\omega\rho}\right) \tag{3.8}$$

I the above equations σ is the dc flow resistivity, Ω is the volume porosity, q^2 is the tortuosity, s_p is the pore shape factor, ρ is the air density, γ is the ratio of specific heats and N_{pr} is the Prandtl number. This model is best suitable for low frequencies and / or large σ:s.

In [17] Thomasson gives another 4-parameter expression for a porous layer with a hard backing:

$$Z_T = \frac{i\sqrt{1+\frac{ic}{\omega}}}{ae^{ib}\tan\frac{e^{ib}\sqrt{1+\frac{ic}{\omega}}\cdot\omega}{2\pi d}} \tag{3.9}$$

where *a*, *b*, *c* and *d* are constants to be determined.

4 Measurement of ground impedance

4.1 General

There are many ways to determine the ground impedance and they can be divided into two categories, propagation measurements and impulse response measurements. Further they can be based on an impedance model, which uses one or more parameters, or they can directly yield the impedance (or reflection coefficient) for each frequency considered.

4.2 Impulse response methods

Impulse response methods use either a correlated measurement with usually a MLS system, or a short impulse from a rifle or electrical spark to measure the impulse response of the ground, see [1] and [5]. This method can directly yield the reflection factor *R* for each frequency. The main problem is that the geometrical system must be very well determined to get the correct phase in the measurements. The position of the ground surface must be known to around 1 mm precision. Such a precision is not realistic for most surfaces. This problem can possibly be avoided by the use of modern signal analysis [14], but it requires complicated equipment and highly qualified personnel.

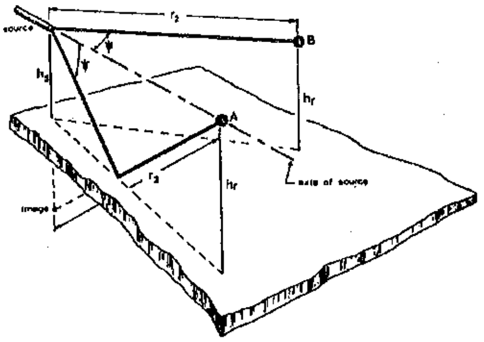


FIG. 2. Two microphone technique to measure simultaneously the direct and reflected impulses.

Figure 4.1
Measurement setup from [1].

MLS measurements [8] have the advantage that the measured signal can be edited in the time domain. This means that unwanted reflections can be deleted, and therefore the measurement can be made fairly close to reflecting obstacles. Another good reason to use MLS-systems is the good signal to noise ratio that can be achieved through averaging.

The use of correlated techniques is not discussed further in this text, since the propagation methods require less complex and expensive equipment, and a faster and cheaper evaluation of the measured data.

4.3 The level difference method

4.3.1 Limitations due to meteorological conditions

One way of establishing the ground attenuation is to measure the propagation between a source and a microphone over the surface in question, see [2] [3] [4] and [6]. Either we have to know the sound power that our source emits, or we can simply measure the level difference between two microphones. In the latter case it is sometimes preferable if the reference microphone could be placed on the ground, but due to strong temperature gradients near the ground, it is usually placed around 0.1 m above the surface.

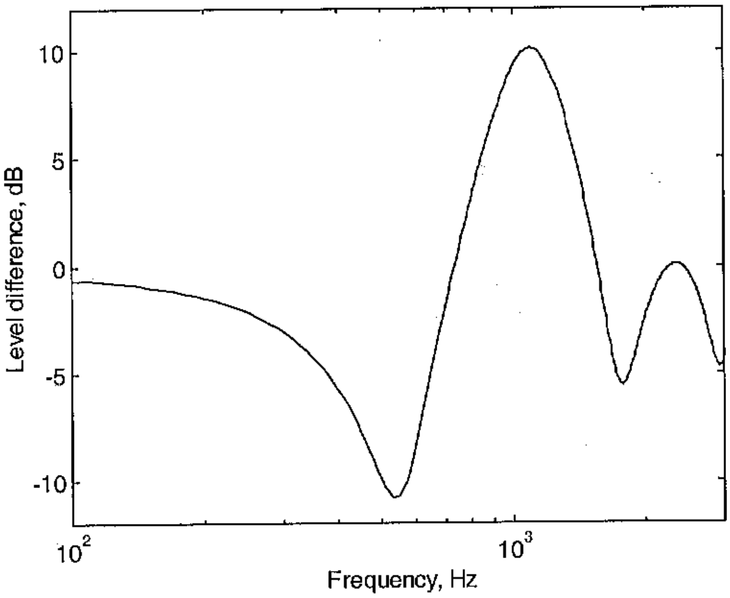


Figure 4.1 Typical level difference plot. Theoretical level difference, hs=.5 m, hr=.5 / .2 m, d=1.75 m

σ=200 000 (3.1)

Early propagation measurements were often conducted at long or intermediate ranges, but then the meteorological effects become very strong, and they will rapidly destroy any information about the ground that the measurement would yield, see [6].

In [3] it is shown that the greatest sensitivity to ground properties is achieved near grazing incidence, but also that near grazing incidence, the effects of turbulence and refraction are severe. It is necessary to compromise between these effects. If we have low microphone positions we get a greater sensitivity to the ground attenuation, but we also get the first minimum point high up in frequency, which means that little or no information can be extracted from frequencies well below this point. High frequencies are more affected by turbulence and refraction. To lower the first minimum point we can increase the distance between the microphones, but again this will increase the effects of turbulence and refraction.

A method to find the effective flow resistivity directly from the minimum point of the spectrum can be found in [3], se figure 4.2. This method is based on the assumption that we can use the plane wave reflection coefficient instead of the spherical one, and still get roughly the same minimum point. For hard surfaces this method is very sensitive to the location of the minimum point, so it is best suited for soft surfaces.

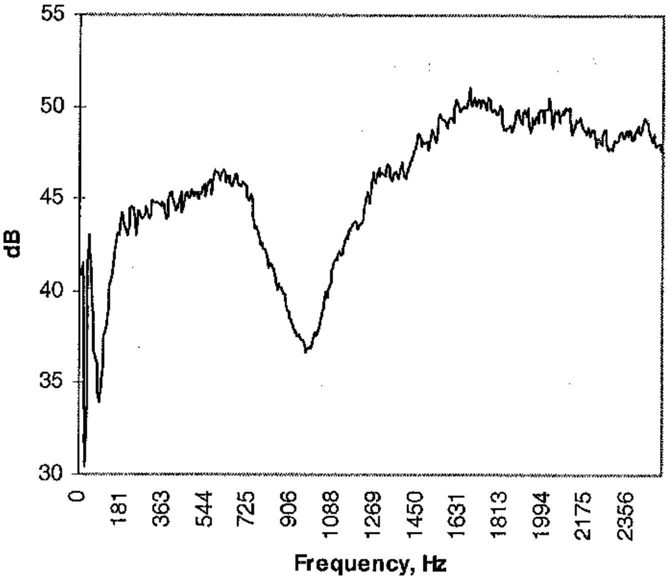


Figure 4.2 Propagation measurement over lawn at SP, hs=hr=0.3 m, d=1.75 m. The minimum in SPL occurs at 969 Hz, which would correspond to an effective flow resistivity of 35700 according to (11) in [3].

4.3.2 Sensitivity to errors in the geometry

In the draft for an ANSI template method for ground impedance [13] a few geometries are proposed. To test the method sensitivity to error in microphone location, ten calculations with slightly different receiver/source heights and distances have been made. The uncertainty in location was set to ±1 cm, uniformly distributed, and the impedance was according to (3.1) with σ=100 000. To test if this could possibly destroy the measurements, another set of calculations with varying σ from 100 000 to 200 000 were made. The results are displayed in figure 4.3 and 4.4.

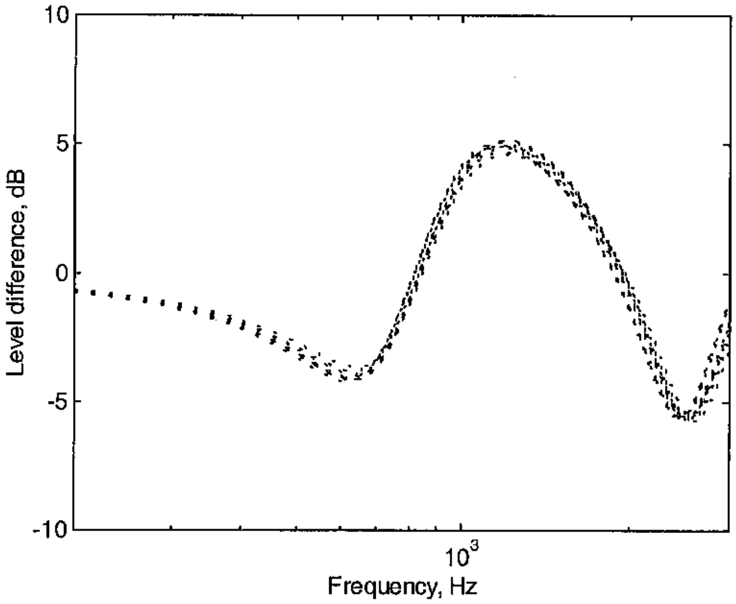


Figure 4.3 Level difference above a soft surface (σ=100 000) with all heights and the distance randomly distributed (± 1 cm). hs=32.5 cm hr=46 cm href=23 cm d=1.75 m

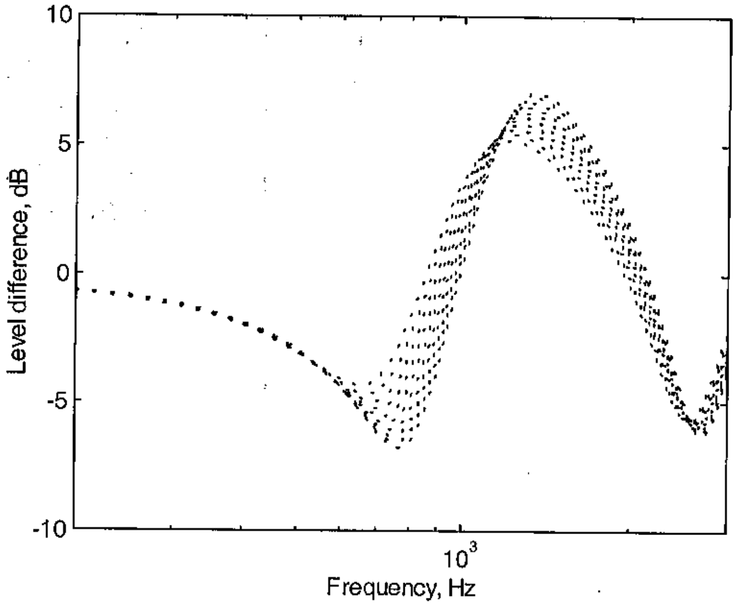


Figure 4.4
Same as figure 4.3 but with heights at nominal value, and σ=100 000 - 200 000

Since the variations in figure 4.4 are much larger than those shown in figure 4.3, we can conclude that the microphone and source placements are not critical if we can keep the placement error less than 1 cm. If we do the same experiment, figure 4.5 and 4.6, but with a hard surface such as asphalt, we will notice that the effects of microphone and source placement are dominant over a change in σ, with a factor 2 which means that we cannot measure this change. On the other hand one might argue that this is not important, both surfaces will act roughly equal under normal sound propagation situations. The same applies for a perfectly reflecting plane, however, so it is evident that this geometry cannot be used to measure high impedances.

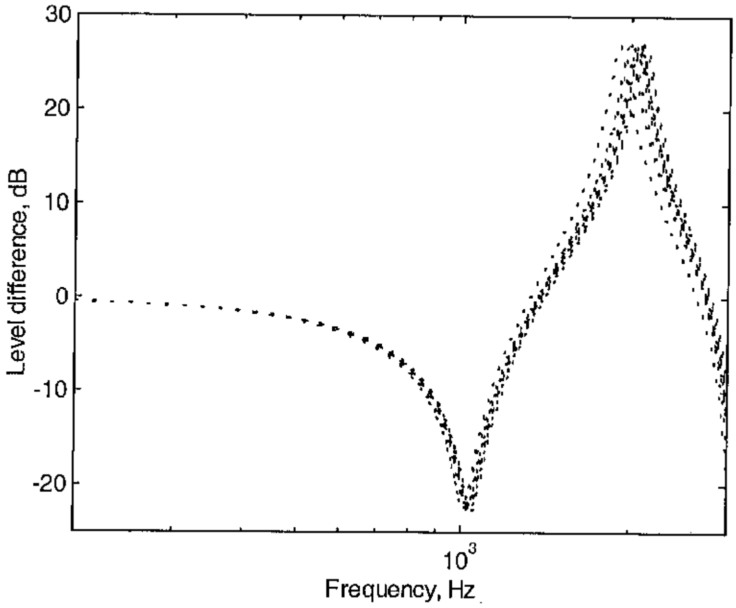


Figure 4.5
Level difference above a hard surface (σ=20 000 000) with all heights and the distance randomly distributed (± 1 cm).
hs=32.5 cm
hr=46 cm
href=23 cm
d=1.75 m

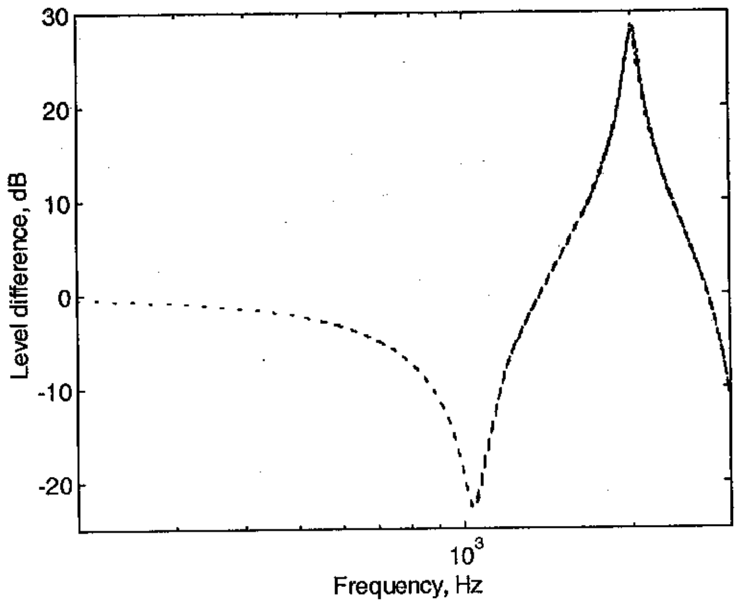
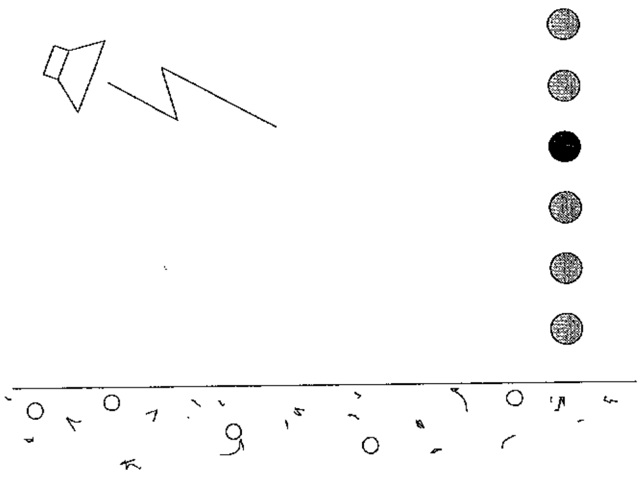


Figure 4.6
Same as figure 4.5, but with heights at nominal value, and σ=20 000 000 - 40 000 000

4.4 The multiple height method

Most methods to measure ground impedance are either based on a correlated measurement technique and are thus sensitive to the uncertainties in the geometry, or are based upon an impedance model. The method proposed here is a plain propagation and level difference technique, but it uses many receiver positions and it will directly yield both the imaginary and the real part of the impedance, without assuming an impedance model. It is however necessary to perform a rather time consuming fitting procedure. This model was used, in principle, in [16].



A typical level difference (with the lowest microphone as the reference) can be seen in figure 4.8. From the previous discussion we have learned that the most information about the ground surface can be found at the minimum point. This time this point is in height instead of frequency, and it can be found for more than one frequency. This means that we do not have to extrapolate the information in frequency via an impedance model, but we can calculate accurate impedance values for a range of frequencies.

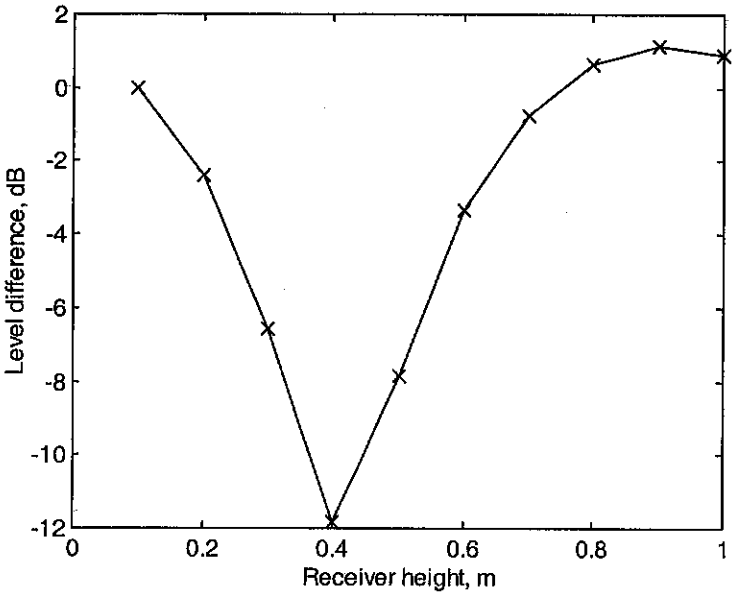


Figure 4.8
Level difference, hs=1.5 m, hr=0.1-1 m, d=4 m. Third octave band 500 Hz. Calculated with σ*=200 000*

Assume that the impedance is constant within a frequency band, octave or third octave band. Compare the measured data with calculations made using $Z=R+iX$ where R and X are swept from 0 to perhaps 20 in small steps. For each point (R,X) calculate the sum of the absolute value of the deviations. This will yield a measure of the error. The result is the point (R,X) where the minimum error is obtained. If the minimum error is achieved on the edge of the searched domain, the value can not be accepted. Either the domain has to be enlarged, or something is wrong in the measurement or the calculation parameters. It can, however, occur for hard surfaces, or very low frequencies, that infinite impedance gives the best fit, so this impedance should also be checked.

Efforts were made to determine the number of measurements needed to determine the impedance (real and imaginary part), but due to the complexity of the expressions involved, no good solution was found. Most likely one can determine the impedance from two level difference measurements (three microphone positions), but the accuracy should increase if the number of microphone positions is increased. To determine if the minimum obtained is the global minimum, and not just a local one, the only method available is to calculate in the entire domain, but experience shows that the error surface is convex except at positions close to the imaginary or real axis. The conclusion was that further efforts are required before a multiple height method can be standardized.

5 Initial measurements

5.1 Measurements with the level difference method

5.1.1 Measurement on a lawn at SP

The source height was 1.5 m, the distance 4 m and the receiver heights were 0.1 and 0.9 m. The impedance model (3.1) was used for the calculations. The flow resistivity σ was swept from 50 000 to 350 000 in steps of 10 000, and for each step the error was calculated according to

$$E = \sum_{200\,Hz}^{2000\,Hz} (\Delta L_{MEASURED} - \Delta L_{CALCULATED})^2 \tag{5.1}$$

Note that this is not exactly the same definition as (2.12), since the error is squared here. The flow resistivity yielding the minimum error is selected as the result. Some examples illustrating the procedure are given in the following.

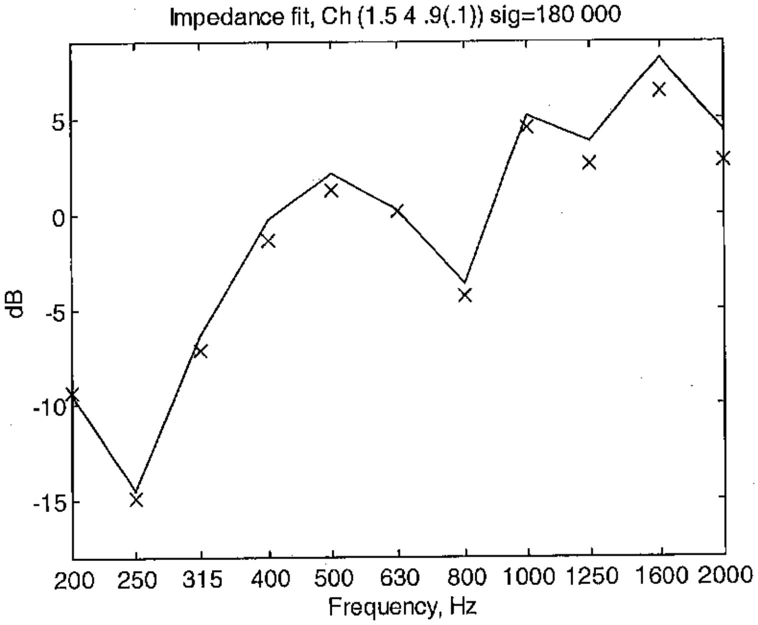


Figure 5.1 Measured and theoretical level difference for the best fit, σ=180 000

x Measured level diff
- Calculated level diff

hs=1.5
d=4
hr=0.9, href=0.1

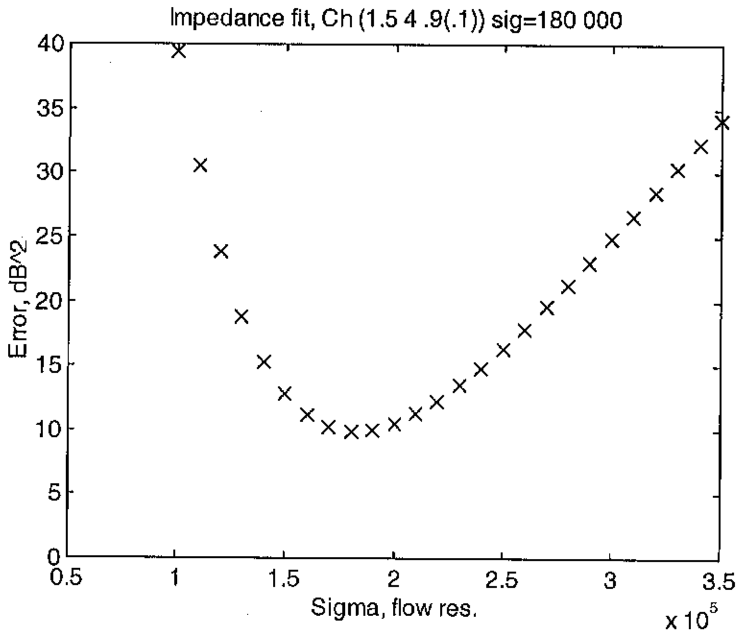


Figure 5.2
Error from (5.1) between measured and calculated level difference. The minimum is at σ=180 000

hs=1.5
d=4
hr=0.9, href=0.1

Note how the error is a very smooth function of σ. If σ changes, the location and level of the first dip is changed, and this has a much stronger effect on the error than random noise. In figure 5.1 we can see that for this geometry the first frequency dip occurs already at 250 Hz, which means that for the high frequencies we will have a lot of dips and peaks, so this is a bad geometry for this situation.

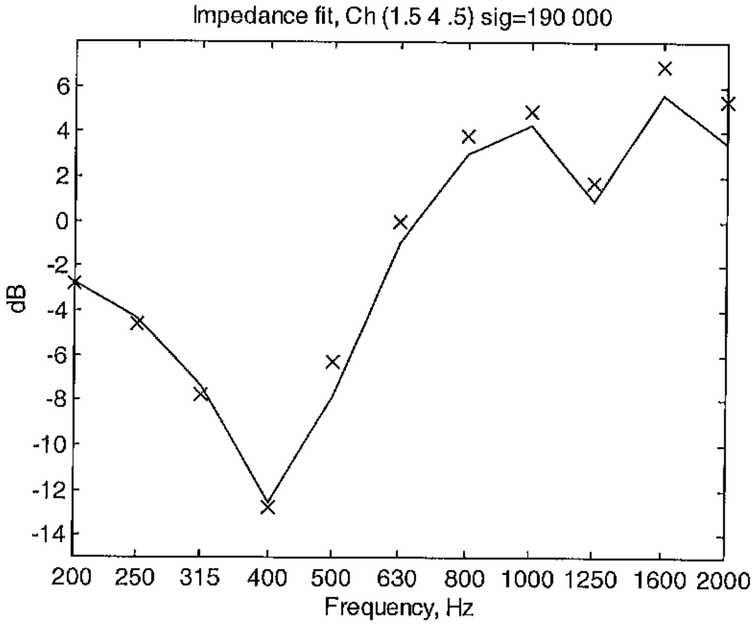


Figure 5.3
Measured and theoretical level difference for the best fit, σ=190 000

x Measured level diff
- Calculated level diff

hs=1.5
d=4
hr=0.5, href=0.1

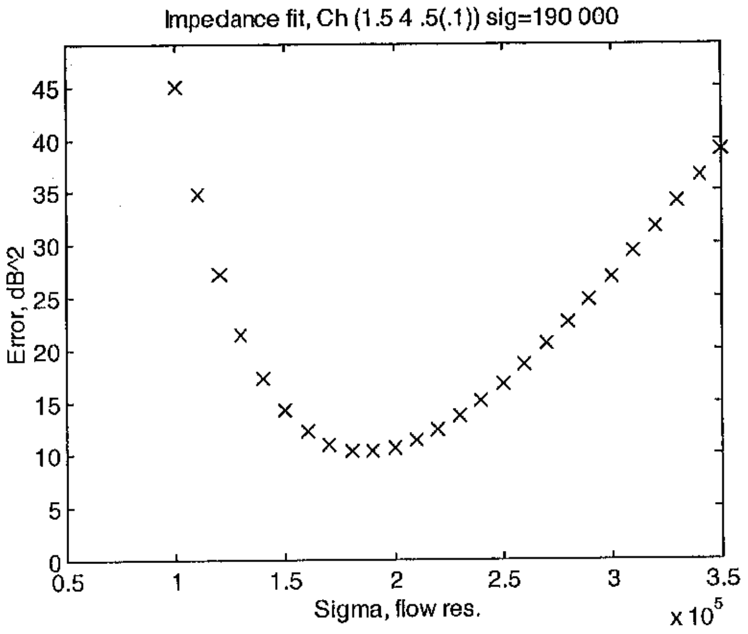


Figure 5.4
Error from (5.1) between measured and calculated level difference. The minimum is at σ=190 000

hs=1.5
d=4
hr=0.5, href=0.1

In figure 5.3 the dip has changed to 400 Hz, and we also get a slight change in our best fit σ from 180 000 to 190 000.

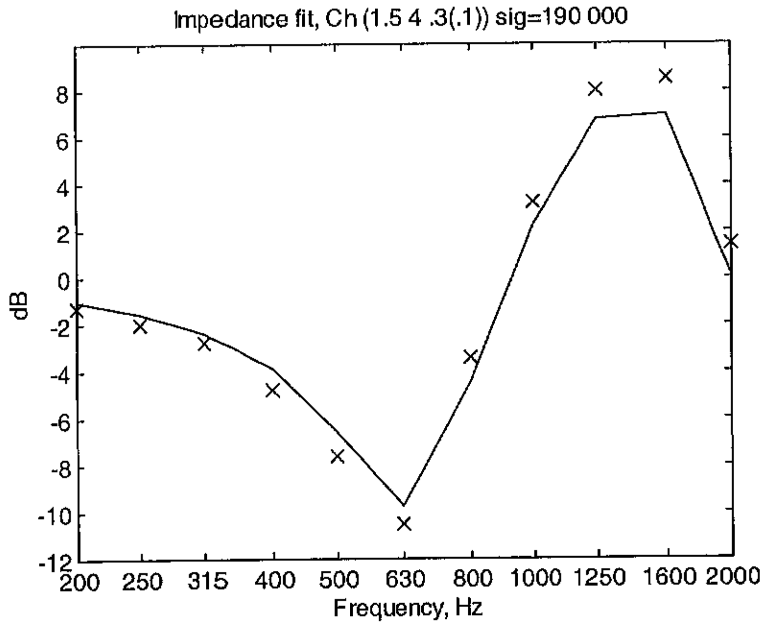


Figure 5.5
Measured and theoretical level difference for the best fit, σ=190 000

x Measured level diff
- Calculated level diff

hs=1.5
d=4
hr=0.3, href=0.1

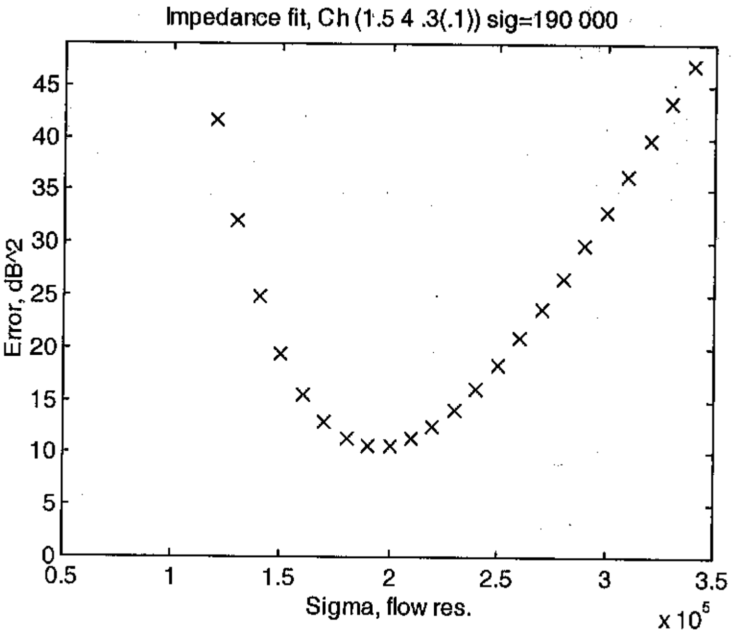


Figure 5.6
Error from (5.1) between measured and calculated level difference. The minimum is at σ= 190 000

hs=1.5
d=4
hr=0.3, href=0.1

The level difference method seems to give good results for this particular surface within the frequency band of interest. The minimum error is quite low (10 dB^2, about 3 dB error with the definition from (2.12)).

5.1.2 Measurement on snow at SP

The measurement site is a grass field at SP in Borås. Temperature at the time of the measurement was -1 °C in the air, and about the same in the snow. The snow depth was 7 cm (± 1 cm), and the ground was frozen. The wind speed was about 1-2 m/s in various directions. All heights were measured relative to the snow surface. The equivalent sound pressure level was measured during 10 s while the source was emitting pink noise in the frequency range of interest (200-2500 Hz).

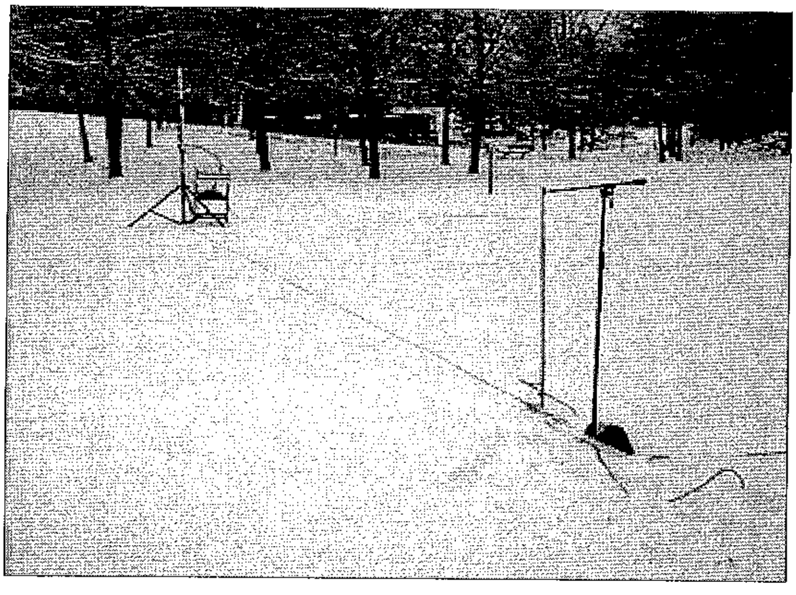


Figure 5.7
The measurement site at SP. The microphones are close to the camera, and the source is further away.

Calculations with the level difference method have been made for two different geometries, and two different impedance models. Geometry S1 is defined in table 5.1.

The measured values (equivalent SPL during 10 s) were compared to calculations in third octave bands with the method described in 2.5. The calculations were made with a step in σ equal to 500, see figure 5.8. First the single parameter model (3.1) was used. This gave a best flow resistivity of 23500, which is within the limits of published values [22]. But the minimum error is 25.1 dB, which seems large. If we use the two-parameter model (3.2) with L=0.07 (the snow depth in meters) we get the best fit for σ=16000 and a minimum error of 17.1 dB.

Table 5.1 Geometry S1

Source height	39.5 cm
Bottom microphone height	22 cm
Top microphone height	52 cm
Horizontal separation source/receiver	529 cm

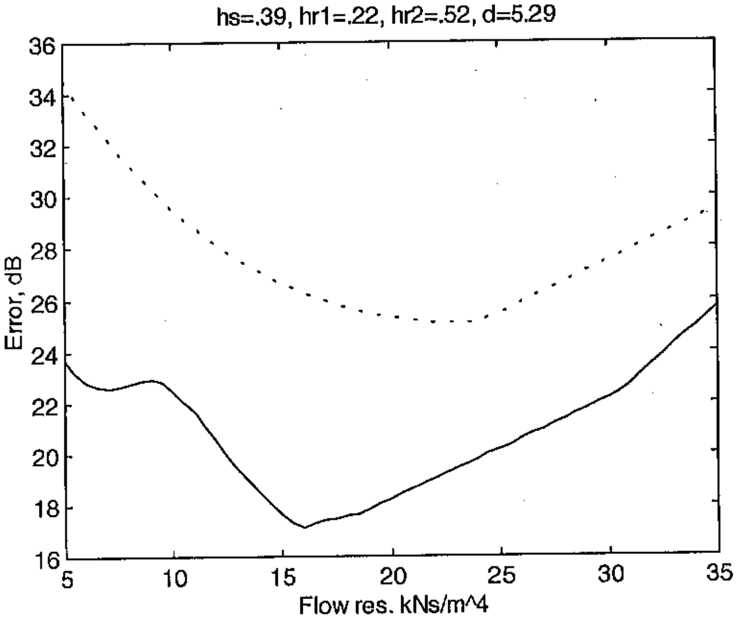


Figure 5.8
Error between measured and calculated level differences. Geometry S1.

--- Model (3.1)
— Model (3.2) with L=0.07

The same procedure was used for geometry S2 defined in table 5.2. The best flow resistivity with model (3.1) was 23 000, and with the two-parameter model (3.2) (L=0.07) σ=17500 produced the minimum error. The errors are quite large again, which can be seen in figure 5.9.

Table 5.2 Geometry S2

Source height	93 cm
Bottom microphone height	22 cm
Top microphone height	52 cm
Horizontal separation source/receiver	768 cm

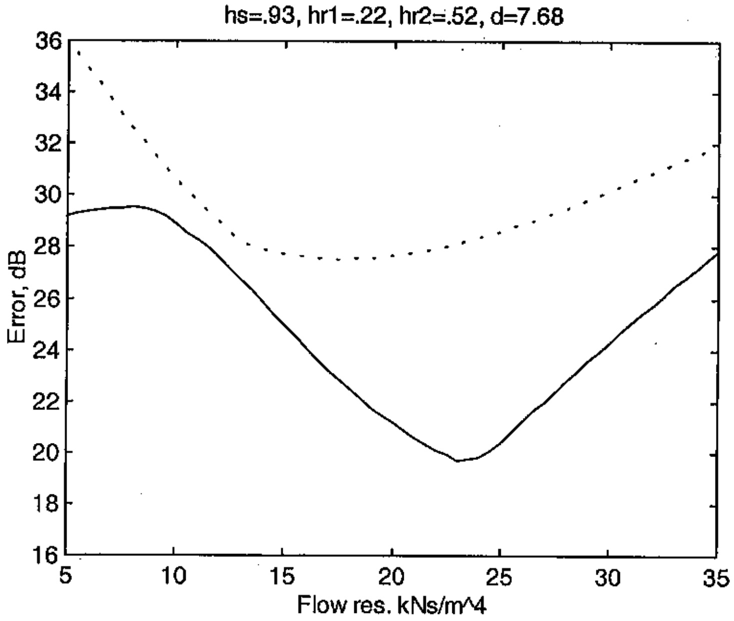


Figure 5.9
Error between measured and calculated level differences. Geometry S2.

--- Model (3.1)
— Model (3.2) with L=0.07

This seems to indicate that both models give a reasonably accurate description of the ground behavior within the frequency range considered here. As can be expected the two-parameter model gives a somewhat smaller error, but the match is far from perfect. These measurements were not repeated to produce a better result, and the distances were a bit higher than the geometry we finally chose which could explain the somewhat bad results compared to similar errors over other terrain types.

5.1.3 Measurement on snow at Viared

The measurements were carried out at Viared glider airfield outside Borås. The temperature was around -2 °C in the air, and slightly lower in the snow. Wind speeds did occasionally reach 5-6 m/s, but care was taken to avoid measuring when the wind speed was high. The snow depth was 7 cm (± 1 cm). All heights were measured relative to the snow surface. The equivalent sound pressure level was measured during 10 s while the source was emitting pink noise in the frequency range of interest (200-2500 Hz).

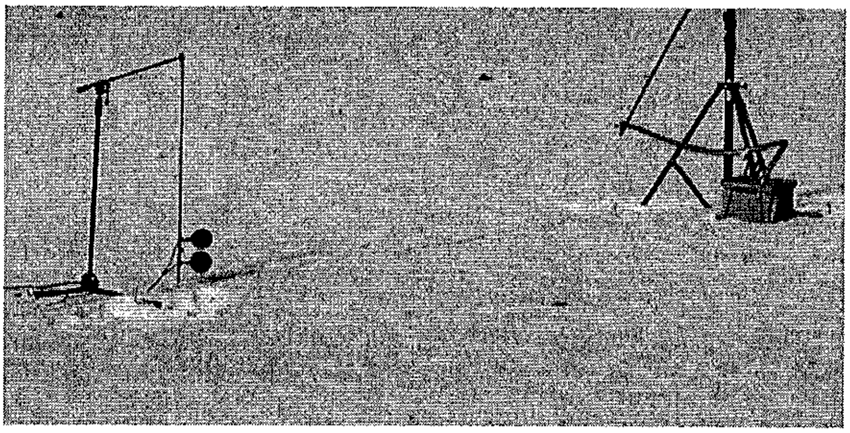


Figure 5.10
The measurement site at Viared. Note that some grass is visible above the snow layer. The snow depth is 7 cm.

Calculations with the level difference method have been made for two different geometries, and two different impedance models.

Table 5.3 Geometry S3

Source height	50 cm
Bottom microphone height	30 cm
Top microphone height	50 cm
Horizontal separation source/receiver	1000 cm

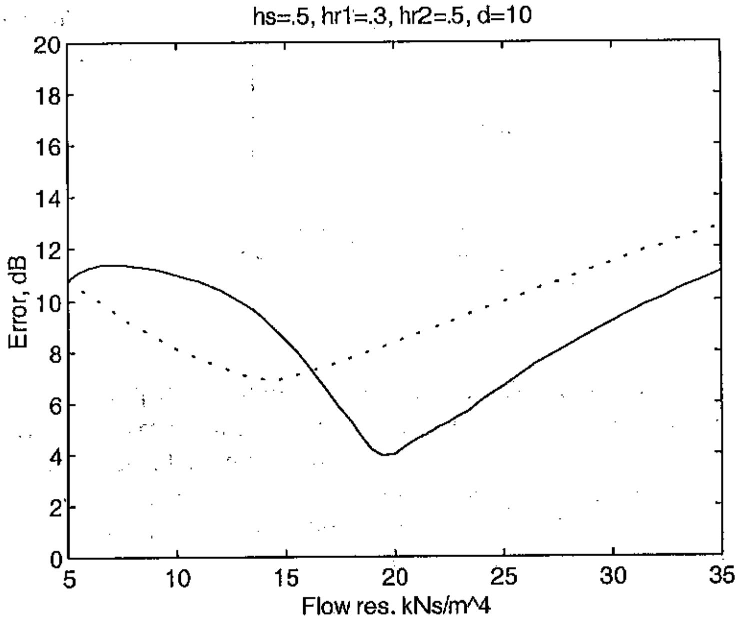


Figure 5.11
Error between measured and calculated level differences. Geometry S3.

--- Model (3.1)
— Model (3.2) with L=0.07

Table 5.4 Geometry S4

Source height	50 cm
Bottom microphone height	30 cm
Top microphone height	50 cm
Horizontal separation source/receiver	400 cm

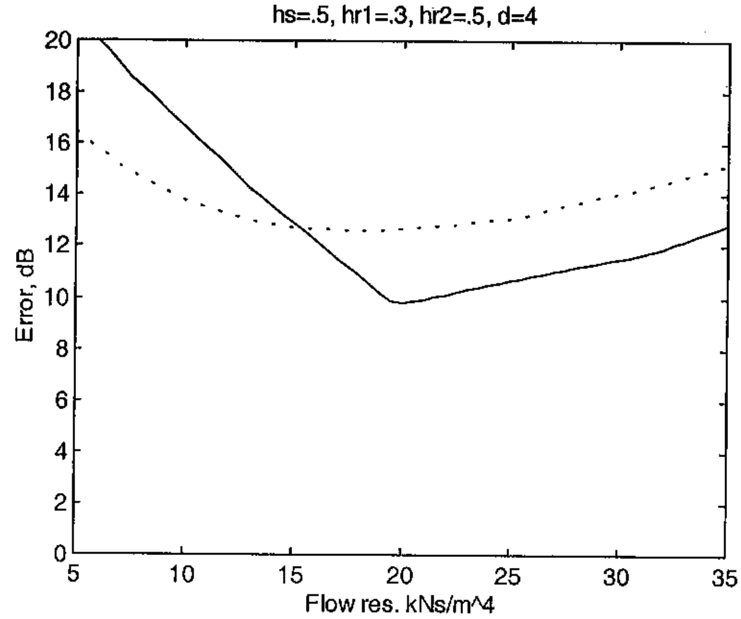


Figure 5.12
Error between measured and calculated level differences. Geometry S4.

--- Model (3.1)
— Model (3.2) with L=0.07

Both S3 and S4 give a value on the flow resistivity of about 20 000 if the two-parameter model (3.2) is used with the snow depth as *L*. The error is a lot larger with geometry S4, but we still get a value, which roughly corresponds to what we can find in literature.

5.2 Measurements with the multiple height method

5.2.1 Test measurement on a lawn at SP

The first measurement with the multiple height method was carried out at a lawn at SP in Borås. The geometry and meteorological conditions can be found in the figure text in figure 5.13.

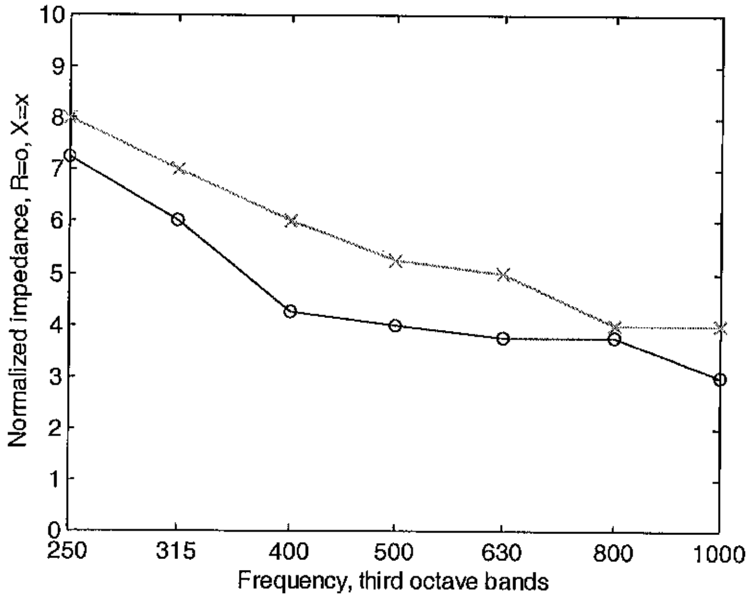


Figure 5.13
Measured impedance, lawn at SP. Temperature around 20°C, less than 1m/s wind and dense cloud cover.
hs=1.5 m
hr=0.1-1.0 m
href=0.1 m
d=4 m

Table 5.5 The values of figure 5.13

Frequency	Re{Z}	Im{Z}
250	7.25	8.00
315	6.00	7.00
400	4.25	6.00
500	4.00	5.25
630	3.75	5.00
800	3.75	4.00
1000	3.00	4.00

In figure 5.14 the measured values are compared to those obtained using the one-parameter model (3.1) and σ= 150 000. Note that in the theoretical values the real part becomes larger than the imaginary one for frequencies higher than 630 Hz, but in the measured case the imaginary part is always larger.

For frequencies lower than 250 Hz we cannot get a good result. This is due to the fact that the impedance is very high at these frequencies, but also to the fact that the method requires much higher receiver positions to capture the minimum in this case. This showed up as impedance values at the edge of the searched domain and/or large errors. For frequencies higher that 1000 Hz, the method gave the minimum error at the edge of the searched domain and also high errors, probably caused by insufficient microphone spacing and meteorological disturbances.

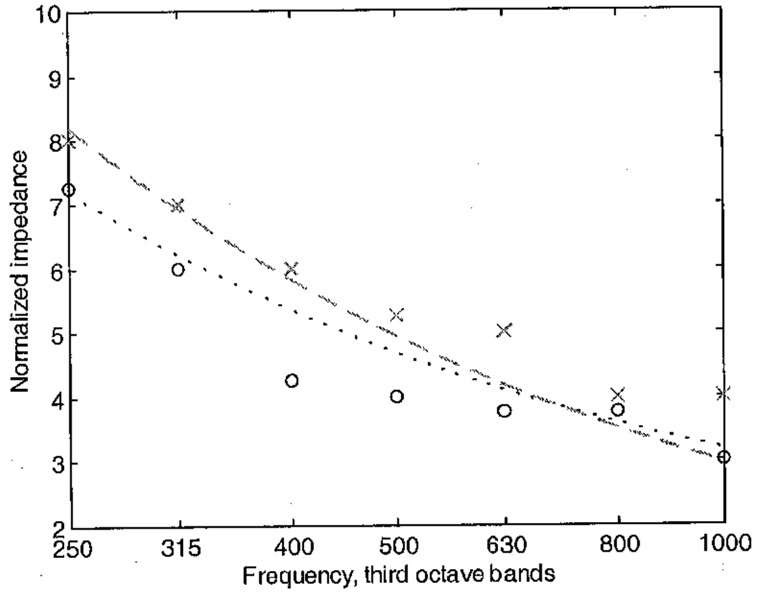


Figure 5.14 Measured and theoretical impedance according to (3.1) with σ=150 000

o Measured real
x and imaginary part

--- Theoretical real
— and imaginary part

6 Considerations for the Nordtest method

6.1 General

The aim of the Nordtest project is to produce a method for the determination of the acoustical impedance of the ground. The method should preferably be simple and straightforward, and of course robust so no difficult interpretations of the results are necessary. Therefore it was decided that correlated measurement techniques were not as interesting, since they require complicated equipment and careful analysis of the measured data.

6.2 Frequency range

For low frequencies we get no information, and for high frequencies the meteorological conditions will severely affect our measurements. Therefore it was decided to study the third octaves from 200 to 2500 Hz

6.3 Basic method to use

The multiple height method has the advantage of not using an impedance model as the level difference method does. This could be valuable if one knows nothing of the type of ground tested. On the other hand none of the measured ground surfaces, with the exception of snow, in chapter 5 or 7 showed any evidence of deviating from the impedance models within the frequency range tested.

The level difference has the advantage of simplicity. With a few simple measurements and comparisons a flow resistivity class, see clause 6.4, can be determined for most surfaces. No information can be obtained on low frequencies since there will simply not be a level difference there for reasonable geometries, and hard surfaces like asphalt can not be measured accurately. This is also true for the multiple height method though, and judging by the current knowledge on impedance measurements a correlated measurement technique of some sort should be the best alternative for very hard surfaces. The level difference also seems to be quite robust. During the verification measurements no group managed to get an erroneous result by more than one flow resistivity class. This is not the case for the multiple height method. A number of the measurements gave very strange results, most notably for low frequencies. The conclusion is that the multiple height method needs further development before it becomes an alternative to the level difference method using predefined impedance models.

6.4 Flow resistivity classes

6.4.1 Why flow resistivity classes?

The calculation of the sound pressure level above an impedance plane described in 2.5 is subject to the requirement that erfc(x) and other complicated functions can be evaluated. A simpler and more reliable approach is to divide the impedance models into classes, and provide tables for the evaluation of measured data. Then no evaluation of erfc(x) would be necessary, and anyone can use a simple spreadsheet program to calculate the errors and determine the correct ground class.

6.4.2 Flow resistivity classes for a wide range of surfaces

The selection of classes is closely linked to the geometry and impedance model used for the measurements and evaluations. A natural choice is to start with the model (3.1). After a number of tests the measurement geometry A, table 6.1, was chosen. Since the flow resistivity varies from about 20 kNs/m^4 to 20 000 kNs/m^4 the most natural approach is to space any classes logarithmically. For a linear spacing the majority of the classes would describe hard surfaces. The error between two level differences is described in 2.6. Two neighboring classes should have an error between them which should be constant for all classes. After some testing it was seen that the classes in table 6.2 produce a useful set of level difference curves for determining which class a measured piece of ground should belong to. The level difference curves corresponding to each class can be seen in figure 6.1.

Table 6.1, Geometry A

Source height	500 mm
Bottom microphone height	200 mm
Top microphone height	500 mm
Horizontal separation source/receiver	1750 mm

Table 6.2, Ground classes for geometry A and impedance model (3.1)

Class number	1	2	3	4	5	6	7	8	9	10	11	12
Flow res kNs/m^4	**10**	**16**	**25**	**40**	**63**	**100**	**160**	**250**	**400**	**630**	**2000**	**20000**

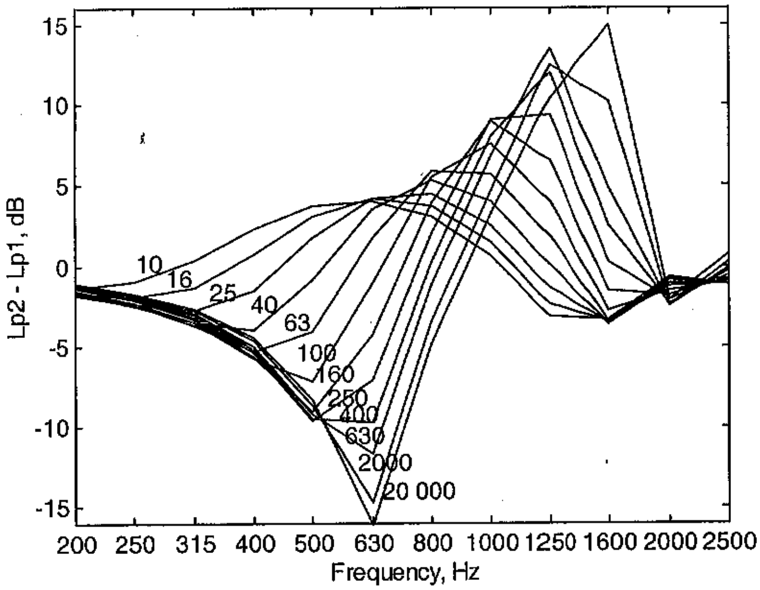


Figure 6.1
Level difference curves with geometry A and the impedance classes from table 6.2

In table 6.3 the error is presented for neighboring classes. This set of classes produce an error of about 10 dB for all steps. Classes 1-10 are logarithmically spaced, and classes 11 and 12 are chosen to give approximately the same error between them.

Table 6.3, Error between two adjacent classes for geometry A and model (3.1)

	10-16	16-25	25-40	40-63	63-100	100-160	160-250	250-400	400-630	630-2000	2000-20000
Error dB	**8.1**	**8.7**	**10.5**	**11.2**	**12.1**	**12.9**	**11.0**	**11.4**	**9.5**	**15.4**	**12.7**

Note that the classes proposed here are based upon the measurement geometry and chosen so that the widest possible range of flow resistivities can be measured. They are not necessarily the best way to classify common ground types to be used for sound propagation calculations, and do not claim to be optimal for anything else than the measurement of ground impedance with their respective geometry.

6.4.3 Flow resistivity classes for hard surfaces

If we want to use another geometry, we need other ground classes. During the evaluation measurements, see chapter 7, a larger geometry was tested for the hard gravel surface. This extra measurement gave only a weak minimum for another set of ground classes, so the extra effort with tables and new ground classes was not considered justified.

6.5 Evaluation of the measurement results

In order to get reproducible measurement results it is necessary to get an objective evaluation of the best fit to a precalculated curve. Some different alternatives were tried but it was concluded that error defined in 2.6 was the best. No strong justification could be found to incorporate frequency weighting or squaring the error before summation and thus decreasing or increasing the importance of single large deviations.

7 Verification measurements of the Nordtest method

7.1 Background and meteorological conditions

During May 13-14 1998 a series of measurements were made in an effort to establish the reliability and versatility of the Nordtest method at Sjömarken outside Borås in the West part of Sweden. The participants were from four Nordic countries: SP from Sweden, VTT from Finland, DELTA from Denmark and SINTEF from Norway. Each participant formed a measurement group with their own separate equipment. All groups used the B&K sound power source type 4205 except SP, which used a source with a 1½" compression driver connected to a flexible tube specially built for the purpose.

All measurement teams had access to a first proposal for Nordtest method. After the measurements the method was discussed and several editorial changes were made. However, the technical contents remained unchanged apart from the fact that the multiple height method and some test geometries were removed from the method. The test results were also used to formulate a clause on the measurement uncertainty. The final proposal for Nordtest method is given in Annex A.

Geometry A was used at all measurement sites by all groups. Some groups made measurements with geometry C and with the multiple height method at some sites.

The weather was mostly clear, with occasional clouds blocking the sun rays. The temperature 1 m above the ground varied from about 16°C at the beginning of the measurements up to 19°C at the last measurement in the afternoon. Wind speeds were generally lower than 1 m/s, with occasional peaks at 2-3 m/s. These conditions were true for both measurement days, with even less wind during the second day.

The results are presented in tables 7.1 - 7.4 where the class which produced the minimum error is presented along with the minimum error and the difference in error to the next higher and lower class (Diff + and -).

7.2 Site A

Site A was a rough grassland. The terrain unevenness was rather large, about ± 5cm and the ground was also a bit concave. This site was selected to test the method when the ground is uneven. The results from the four groups are presented in table 7.1. Diff + is the difference between the error of the next higher class and the error of the best class, and Diff - is the same but for the next lower class.

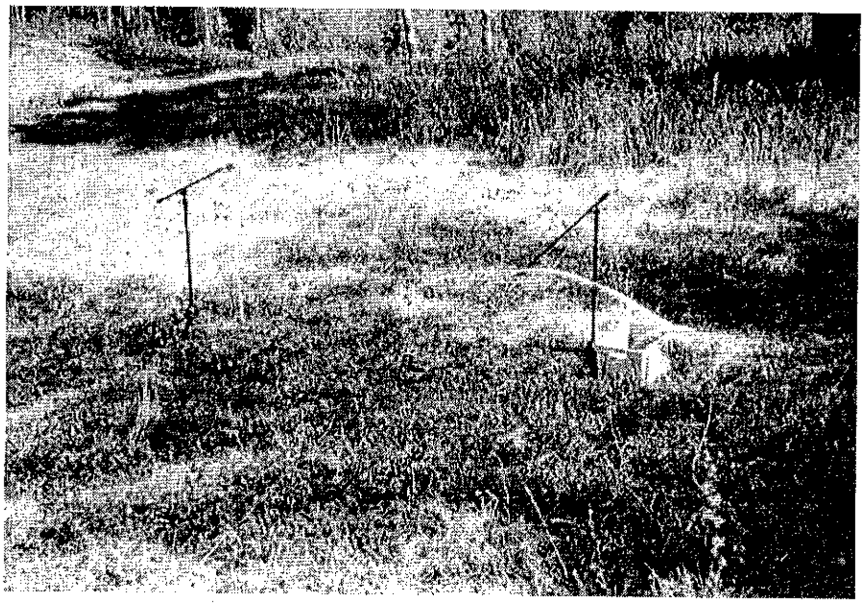


Figure 7.1
Measurement site A

Table 7.1 Results from site A.

	SP	DELTA	VTT	SINTEF
Class:	**100**	**160**	**63**	**100**
Min error:	10.7	12.2	19.5	11.9
Diff +	7.5	9.1	1.4	7.7
Diff -	7.3	0.8	7.2	5.8

7.3 Site B

Site B was the start of an exercise track consisting of earth mixed with sawdust. The surface was rather even. A few small hills made out of sawdust surrounded the measurement site. All four groups got the same flow resistivity class, and the errors were quite small. This indicates that this was an easy ground to measure, and also that the "true" flow resistivity is quite close to the class value of 250 kNs/m^4.

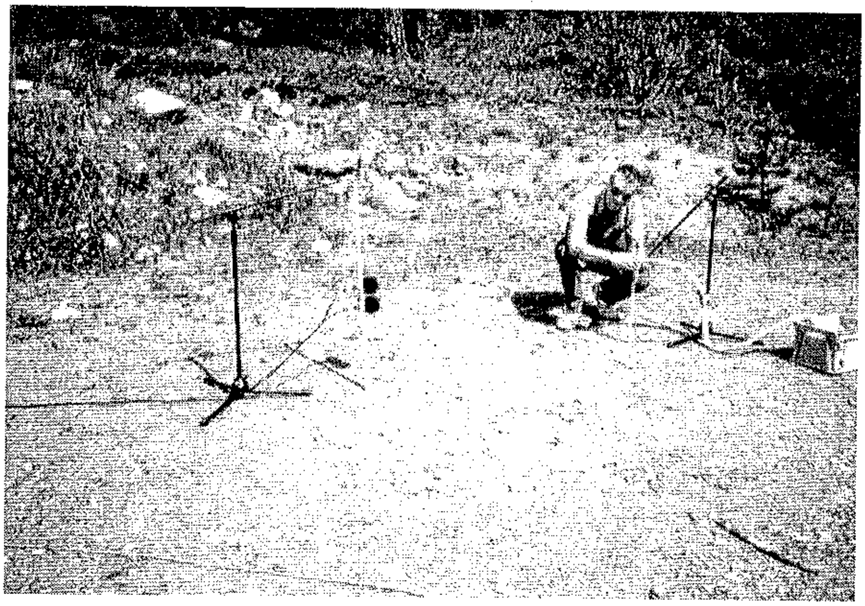


Figure 7.2
Measurement site B

Table 7.2 Results from site B.

	SP	DELTA	VTT	SINTEF
Class:	**250**	**250**	**250**	**250**
Min error:	5.0	7.4	8.5	6.0
Diff +	4.8	4.1	1.0	10.1
Diff -	9.3	7.7	9.3	5.6

7.4 Site C

Site C was a football field with a well cut grass vegetation. Three groups got the 630 class, and one the 400 class. A grass field is usually expected to be a bit "softer", around 200 kNs/m^4, but the soil was rather densely packed.

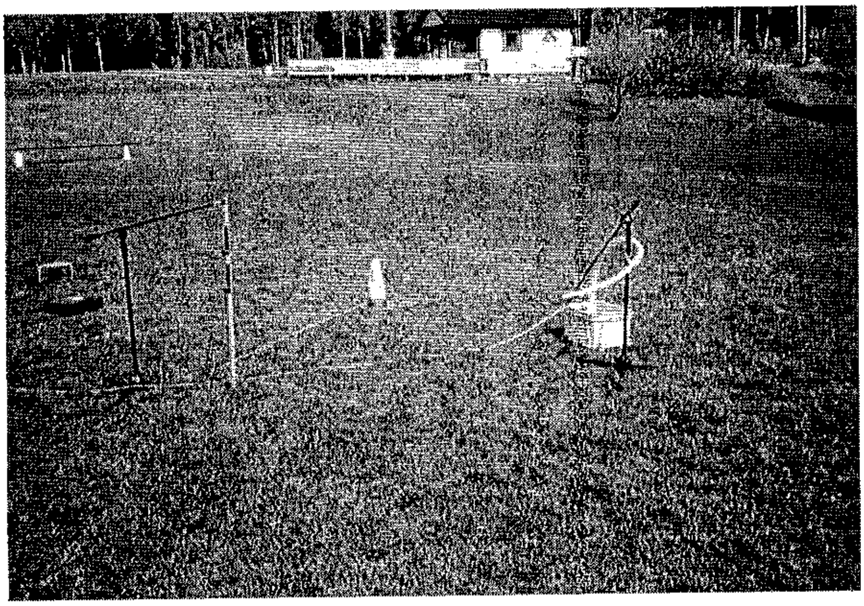


Figure 7.3 Measurement site C

Table 7.3 Results from site C.

	SP	DELTA	VTT	SINTEF
Class:	**630**	**630**	**400**	**630**
Min error:	10.1	5.2	7.2	8.2
Diff +	3.2	10.5	3.3	14.8
Diff -	6.3	5.2	7.9	0.2

7.5 Site D

Site D consisted of a dense gravel surface used for parking cars and, in winter time, as a football field. This is obviously a very hard surface, and it is questionable if the method can discriminate between very hard surfaces. All groups got 2000 as the class, the second hardest of the classes.

Figure 7.4
Measurement site C

Table 7.4 *Results from site D.*

	SP	DELTA	VTT	SINTEF
Class:	**2000**	**2000**	**2000**	**2000**
Min error:	10.2	10.1	13.9	9.2
Diff +	12.4	5.0	7.7	7.8
Diff -	2.7	7.8	1.3	4.6

7.6 Extra measurements

7.6.1 Geometry C at site D

The group from DELTA made a measurement using geometry C on the measurement site D. Geometry C is expected to give a somewhat better resolution for hard surfaces, but also to be a bit more sensitive to meteorological effects since the distance is larger. Only two repetitions were made, and the result can be found in table 7.5. Note that we get the class 3200, but the separation from the neighboring classes is poor, about 1 dB. In other words, using geometry C gives only a limited amount of extra information for hard surfaces.

Table 7.5 *Results for the measurements on site D with geom. C*

Flow res class	Error, dB
400	**37.5**
630	**28.1**
1000	**21.9**
2000	**10.8**
3200	**9.7**
6400	**10.7**
20000	**12.6**

7.6.2 Measurements on a few forest floors

The team from SP made some extra measurements on terrain in the surroundings to establish the flow resistivity class of some different forest floors. The first, called site E, is a sandy forest floor. The second, called site F, is a soft forest floor covered with pine needles. The third, site G, is a soft forest floor with moss and small blueberry bushes. The meteorological conditions were as above, and all measurements used geometry A.

Table 7.6 Results from the forest floors.

	E	F	G
Class:	**2000**	**160**	**40**
Min error:	7.2	5.0	4.5
Diff +	7.4	6.7	6.7
Diff -	1.4	4.9	7.0

The results suggest that there is a large variation in flow resistivity depending on the type of forest floor.

8 Some additional measurements with the Nordtest method

8.1 Typical Nordic ground types

After the preliminary method was ready, a number of measurements were carried out by SP, SINTEF and DELTA. The meteorological conditions varied during the different measurements, but were within the limits of the proposed standard. Most ground types were moist but not saturated with water. The results can be found in table 8.1, and for those measurements were photos are available, they can be found in 8.3. The results from the verification measurements (SP) are also presented in the same table.

*Table 8.1 Results of measurements carried out by SP and SINTEF with the proposed method. * indicates that photos can be found in chapter 7.*

Description	Flow res. Class kNs/m^4	Min. Error	Max std.dev	Photo nr
Gravel road, small stones	**2000**	**8.1**	**1.9**	**1**
Gravel road, stones and dust	**2000**	**6.9**	**2.3**	**2**
Gravel, earth and sparse grass	**630**	**6.9**	**1.7**	**3**
Pasture	**250 (160)**	**14.3**	**2.7**	**4**
Earth and bark, sparse vegetation	**100**	**8.6**	**2.0**	**5**
Old gravel field with sparse vegetation	**2000 (20 000)**	**10.5**	**2.5**	**6**
Earth covered with leaves and twigs	**160 (250)**	**12.9**	**2.8**	**7**
Rough grassland	**100**	**10.7**	**3.32**	*
Earth mixed with sawdust	**250**	**5.0**	**1.52**	*
Grass, soccer field	**630 (2000)**	**10.1**	**2.20**	*
Gravel parking lot	**2000 (630)**	**10.2**	**1.37**	*
Sandy forest floor	**2000 (630)**	**7.2**	**2.83**	-
Soft forest floor covered with pine needles	**160**	**5.0**	**2.86**	**8**
Soft forest floor with blueberry greens and moss	**40**	**4.5**	**1.76**	**9**
Lawn	**250 (400)**	**11.0**	**2.0**	**10**
Relatively dense soil sparsely covered by grass and other low greens.	**630**	**7.9**	**1.6**	**11**
Short grass, green moss and blueberry greens	**40**	**13.6**	**2.8**	**12**
Peat or turf area, homogeneous organic material	**100**	**6.4**	**3.6**	**13**
Lawn I, seldom stepped on	**250**	**8.5**	**2.2**	-
Forest floor covered by weeds	**63 (100)**	**9.2**	**1.3**	-
Dense shrubbery, 20 cm high	**100**	**11.0**	**2.1**	-
Mixed paving stones and grass	**630 (2000)**	**10.9**	**1.0**	-
Agricultural field I	**160 (250)**	**13.3**	**3.0**	-
Agricultural field II, stubble field	**400 (250)**	**7.7**	**2.3**	-
Gravel, parking lot	**400 (630)**	**12.3**	**2.4**	-
Lawn II, moderately stepped on	**250 (160)**	**14.6**	**0.8**	-
Lawn III, heavily stepped on	**400 (250)**	**10.6**	**2.2**	-
Hard soil	**2000 (630)**	**11.3**	**1.4**	-
Pasture	**250 (160)**	**8.9**	**2.0**	-

8.2 The effect of surface roughness

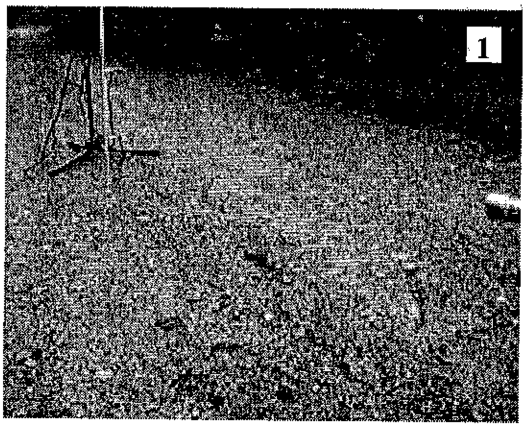
In order to study the effect of surface roughness on the measured ground class, a number of measurements were carried out at a sandy beach located at Viaredssjön. First a measurement was made without disturbing the sand, and after this a number of rough or flat surfaces were created in the sand and measured. The results can be found in table 8.2, and photos of some of the surfaces can be found in 8.3. The temperature was 11°C and the wind was 0-2 m/s.

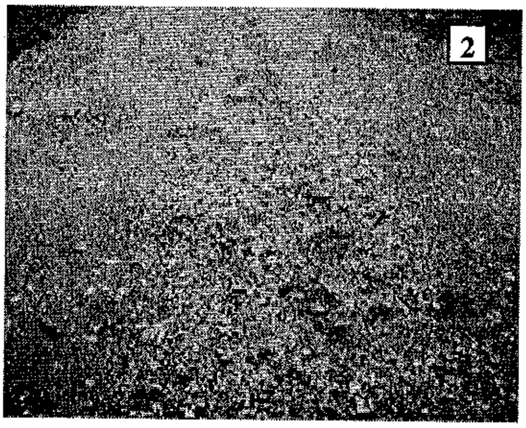
The results indicate that the surface impedance was strongly affected by the rearranging of the sand, from ground class 400 to 160. The random pattern and the hills seem to lower the measured ground class somewhat. This is most likely an effect of the surface roughness as described in [19].

Table 8.2 Results of measurements carried out by SP at Viaredssjön. Note that only the first measurement used four repetitions, all others were made with a fixed geometry.

Description	Flow res. Class kNs/m^4	Photo nr
Sandy beach, untouched	**400 (250)**	-
Small hills (5 cm peak to peak) at 20cm intervals	**160**	**14**
Small hills (7 cm peak to peak) at 20cm intervals	**100 (160)**	-
Small hills (9 cm peak to peak) at 20cm intervals	**100**	-
Sand, carefully re-flattened after hill experiment	**160 (250)**	-
Random pattern with about 4 cm peak to peak	**100 (160)**	**15**
Sand, carefully re-flattened after random pattern experiment	**160**	-
Square pattern, carefully packed sand	**160**	**16**

8.3 Photos from the measurement sites


1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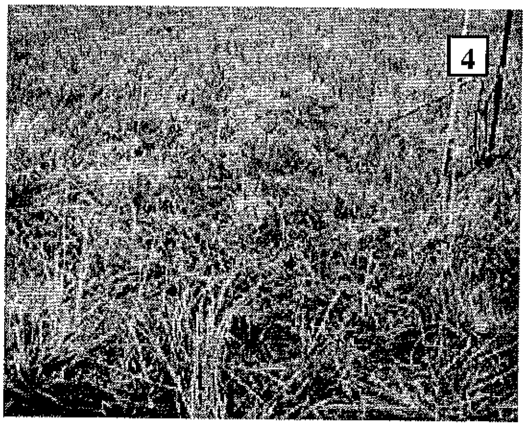
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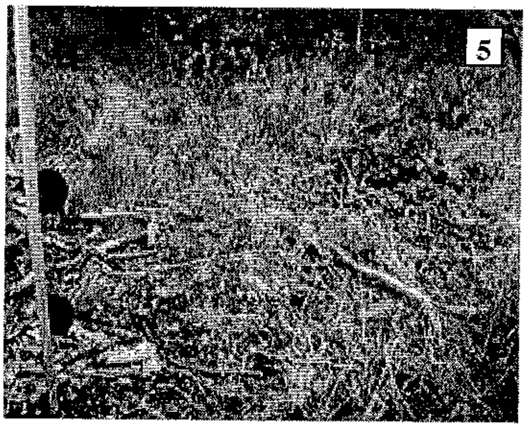
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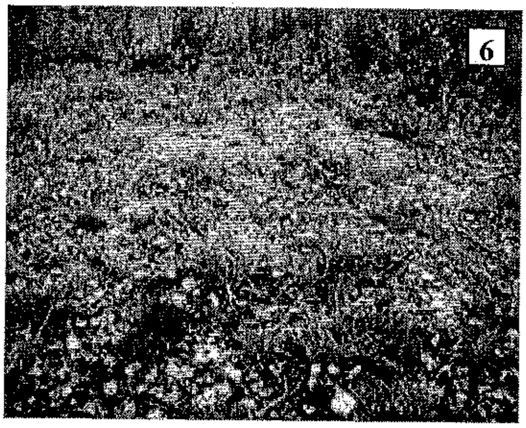
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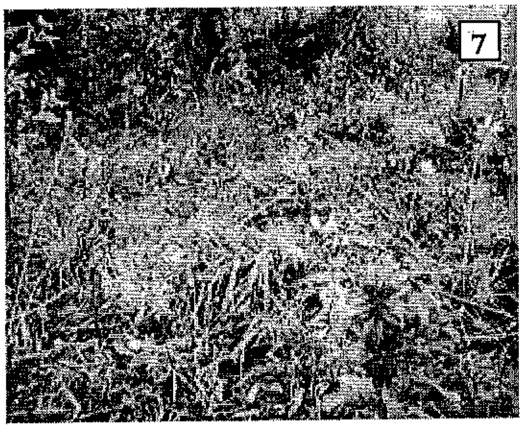
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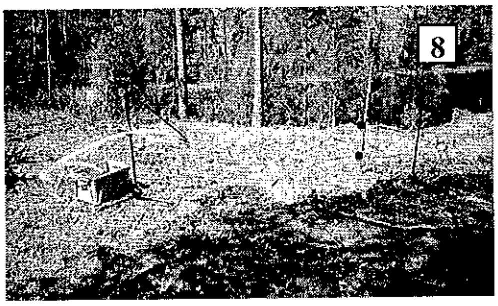
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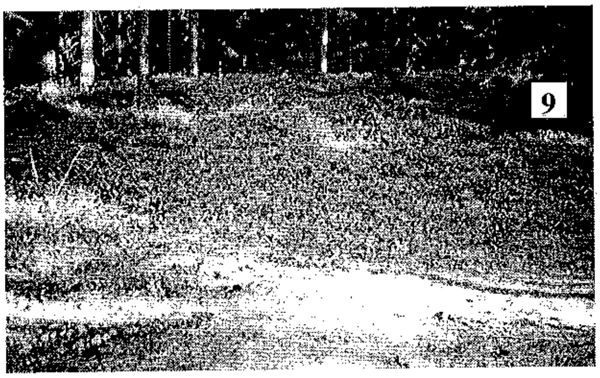
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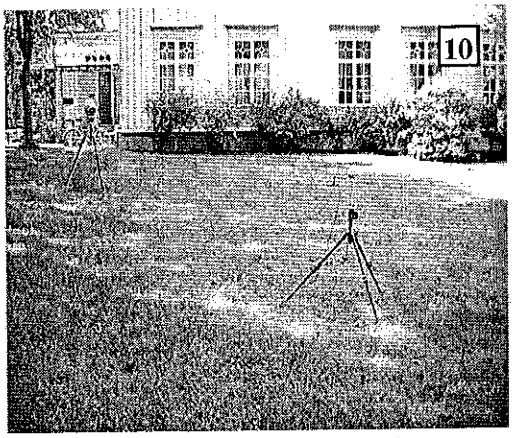
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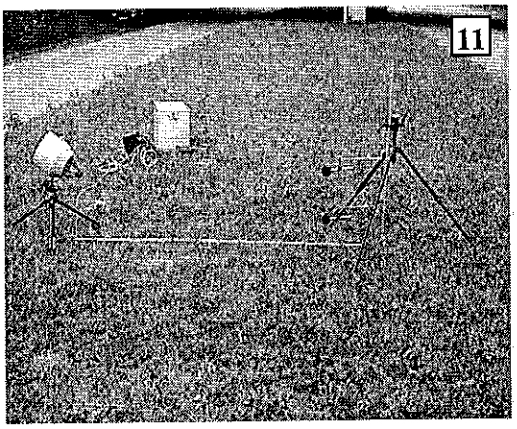
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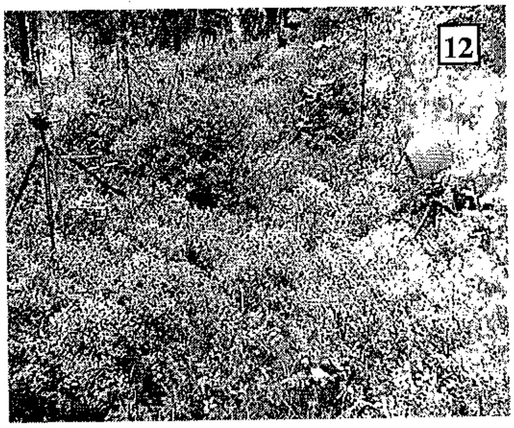
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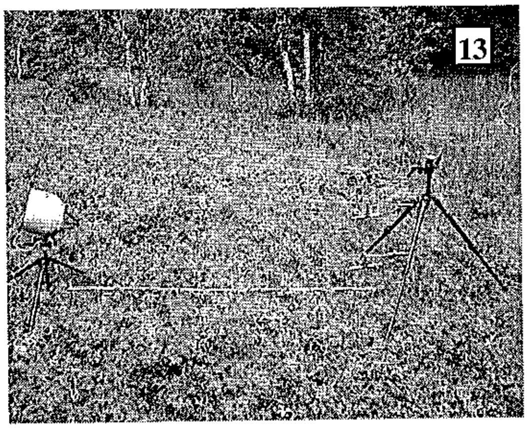
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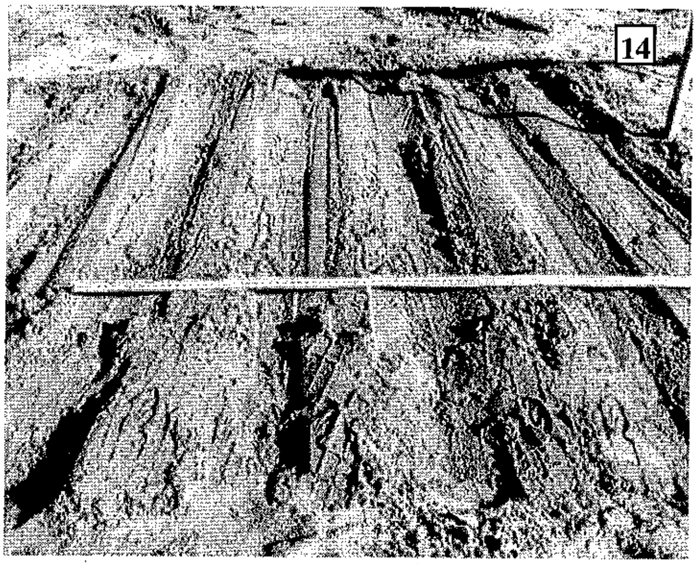
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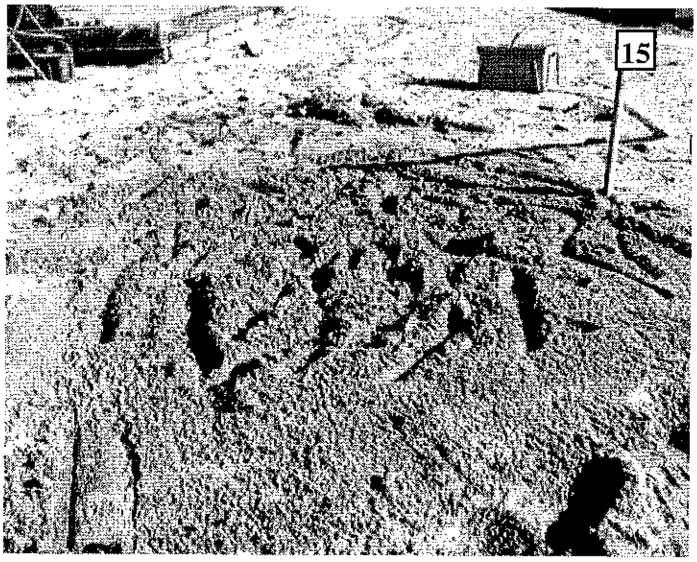
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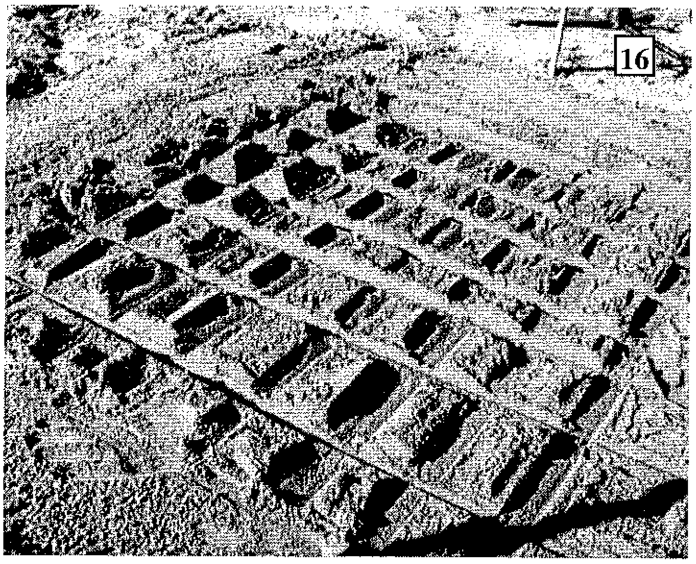
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9 References

[1] Soil impedance measurements by an acoustic pulse technique
C. G. Don, A. J. Cramond
J. Acoust. Soc. Am. 77(4), 1985

[2] Ground characterization by short-range propagation measurements
H.M. Hess, K. Attenborough, N.W. Heap
J. Acoust. Soc. Am. 87(5), 1990

[3] A note on short-range ground characterization
K. Attenborough
J. Acoust. Soc. Am. 95(6), 1994

[4] An improved procedure for determination of ground parameters using level difference measurements
James M. Sabatier, Richard Raspet, Carl K. Frederickson
J. Acoust. Soc. Am. 94(1), 1993

[5] A Pulsed Level Difference Technique for Ground Characterization
David W. Craig, James M. Sabatier
Applied Acoustics 44, 1995

[6] Measurement and analysis of sound propagation over lawn
Kohei Yamamoto, Mitsuyasu Yamashita
J. Acoust. Soc. Jpn. 15, 1994

[7] Acoustic wave propagation along a snow surface
Masaki Hasebe
J. Acoust. Soc. Jpn. 6, 1985

[8] Outdoor Sound Propagation Measurements Using an MLS Technique
Kurt Heutschi, Allan Rosenheck
Applied Acoustics 51, 1997

[9] Acoustical Impedance Models for Outdoor Ground Surfaces
K. Attenborough
Journal of Sound and Vibration 99(4), 1985

[10] Impedance models for grass-covered ground
R. J. Donato
J. Acoust. Soc. Am. 61(6), 1977

[11] Propagation of noise along a finite impedance boundary
C. I. Chessel
J. Acoust. Soc. Am. 62, 1977

[12] Effects of ground cover on the propagation of sound through the atmosphere
L. N. Bolen and H. E. Bass
J. Acoust. Soc. Am. 69(4), 1981

[13] Template Method for Ground Impedance
ANSI S1.x - 199x, Third draft 03/1997
(Draft - Not approved)

[14] Determination of a reflecting surface by Hilbert transform method
Yasushi Miki
J. Acoust. Soc. Jpn. 11, 5, 1990

[15] Acoustics- An Introduction to Its Physical Principles and Applications
A. D. Pierce
McGraw-Hill 1981, ISBN 0-07-049961-6

[16] Sound propagation over ground with and without barriers
Hans G. Jonasson
Lund Institute of Technology, 1971

[17] Sound propagation above a layer with a large refraction index.
Sven-Ingvar Thomasson
J. Acoust. Soc. Am. 61, 1977

[18] Acoustic Properties of Fibrous Absorbent Materials
M. E. Delaney, E. N. Bazley
Applied Acoustics 3(2), 1970

[19] Grazing incidence propagation over a soft rough surface
James P. Chambers, James M. Sabatier, and Richard Raspet
J. Acoust. Soc. Am. 102(1), 1997

[20] A note on the calculation of sound propagation along an impedance boundary
C. F. Chien, W. W. Soroka
J. of Sound and Vibration 69, 1980

[21] C. I. Chessel
Noise propagation along an impedance boundary
J. Acoust. Soc. Am. 62(4), 1977

[22] Handbook of Acoustics
Malcom J. Crooker (Edited by)
John Wiley & Sons 1998, ISBN 0-471-25293-X

[23] Acoustics
L. L. Beranek
ISBN 0-88318-494-X

[24] Measurement method for acoustic impedance of ground
S. Lindblad, K. Rasmussen, S. Storheier, H. Tuoiminen
NORDTEST project 362-82, 1983

[25] The surface impedance of grounds with exponential porosity profiles
R. Raspet, J. M. Sabatier
J. Acoust. Soc. Am. 99(1), 1996

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Annex - Proposal for Nordtest method

Ground surfaces: Determination of the acoustic impedance

Contents

1 SCOPE AND FIELD OF APPLICATION

1.1 General

This NORDTEST method specifies how to determine the normalised specific acoustic impedance of flat ground surfaces outdoors in situ. It yields one or several flow resistivity classes the values of which can be translated into the real and imaginary part of the specific acoustic impedance to use for outdoor sound propagation calculations. This NORDTEST method is not suitable for the evaluation of ground impedances below 200 Hz or above 2500 Hz.

1.2 Measurement uncertainty

The measurement uncertainty is estimated to be ± 1 flow resistivity class.

Note The measurement uncertainty has been estimated from comparison measurements carried out on 4 different ground surfaces by 4 different Nordic laboratories.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Nordtest method. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Nordtest method are encouraged to investigate the possibility of applying the most recent edition of the standards indicated below. Members of IEC and ISO maintain registers of currently valid international standards.

IEC 651:1979, *Sound level meters.*

IEC 804: 1985, *Integrating-averaging sound level meters.*

IEC 942:1988', *Sound calibrators.*

IEC 1260:1995. *Electroacoustics, Octave-band and fractional-octave band filters.*

3 Definitions

3.1 specific acoustic impedance, Z_s:

Ratio of surface pressure to particle velocity directed into the ground at the surface, in Nsm^{-3}.

3.2 normalised specific acoustic impedance, Z_n:

Ratio of specific acoustic impedance of the ground to the characteristic impedance of air,

$$Z_n = \frac{Z_s}{Z_c} \qquad (1)$$

where $Z_c = \rho_0 c$, dimensionless. ρ_0 is the density of air (1,2 kg/m^3)and c the speed of sound.

3.3 effective flow resistivity, σ:

The effective flow resistivity, Ns/m^4, is used here as a parameter into the impedance models described in clause 5.

3.4 frequency range of interest:

For general purposes, the frequency range of interest includes the 1/3-octave bands with midband frequencies from 200 Hz to 2500 Hz.

Note. The frequency range of interest may be expanded in either direction but this Nordtest-method may then not yield accurate results.

4 Instrumentation

4.1 General

Within the frequency range of interest the sound source shall be a loudspeaker, omnidirectional within 1 dB within ± 30°. The microphones shall be omnidirectional within 1 dB within ± 45°. Both microphones shall be fitted with windscreens during the measurements.

The measurement equipment shall meet the requirements of a class 1 instrument according to IEC 651 and IEC 804 and the filters shall meet the requirements of IEC 1260.

4.2 Calibration

During each series of measurements, apply a sound calibrator with an accuracy of ±0,3 dB (class 1 according to IEC 942) to the microphone for checking the calibration of the entire measuring system at one or more frequencies over the frequency range of interest.

Verify the compliance of the calibrator with the requirements of IEC 942 once a year and the compliance of the instrumentation system with the requirements of IEC 651 at least every two years in a laboratory making traceable calibrations.

Record the date of the last check and confirmation of the compliance with the relevant IEC standard.

5 Impedance models

For this NORDTEST method it is necessary to have one (or more) theoretical models describing the frequency dependence of the acoustic impedance of the ground. The models given below have been used to calculate the tables in annex B and the equations are only needed when the ground impedance has to be calculated as a function of frequency.

As one-parameter model the following model (time dependence $e^{-i\omega t}$) shall be used

$$Z_n = 1 + 9{,}08\left(\frac{1000f}{\sigma}\right)^{-0{,}75} + i11{,}9\left(\frac{1000f}{\sigma}\right)^{-0{,}73} \qquad (2)$$

Note. This model is less accurate for low frequencies.

If we have a relatively soft layer on top of a hard surface, such as snow on frozen ground, the following modified one-parameter model shall be used:

$$Z_n = Z_{n1} i \cot(Lk) \qquad (3)$$

$$k = \frac{2\pi f}{c}\left[1 + 10{,}8\left(\frac{1000f}{\sigma}\right)^{-0{,}70} + i10{,}3\left(\frac{1000f}{\sigma}\right)^{-0{,}59}\right] \qquad (4)$$

Z_{n1} is the impedance obtained from equation (2), and L is the best estimate of the porous layer depth. Note that source and microphone heights shall be measured from the top of the soft layer.

6 Test procedure

6.1 Principle

The method uses two fixed microphone positions, the bottom and the top microphone respectively.

The sound pressure level is measured at two different heights above the ground at a specified distance from a loudspeaker at a specified height above the ground. The measured data are used to obtain a best fit to one of a number of calculated curves. The result is the flow resistivity class.

6.2 Requirements on the test site

The test site shall be flat within ± 50 mm and no vertical reflecting objects are allowed within 10 times the distance of separation between source and receiver. The ground shall be in the condition desired for the measurements. It can be dry, wet, snowcovered, frozen or in any other conditon provided that there is an accurate description of it in the test report.

Note It may be difficult to comply with the qualification requirements of clause 6.8 if the ground surface is concave or convex over the test site.

6.3 Requirements on meteorological conditions

To minimize turbulence due to thermal and wind gradients it is recommended to carry out the measurements when the sky is overcast and the wind speed low. If there is a stable wind direction locate the measurement line at an approximately right angle to the wind direction, see figure 1.

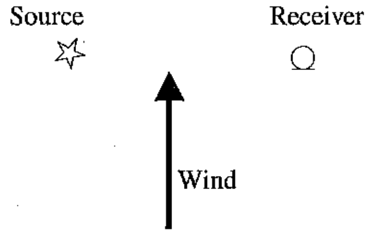

Figure 1 Location of source and receiver in relation to dominant wind direction.

The wind speed shall not exceed 5 m/s when measured at a height of 1 m above the ground.

6.4 Recommended geometry

The best locations of the sound source and the microphone positions will depend on the acoustic properties of the ground and the frequency range of interest. The locations to use with this Nordtest method are given in table 1.

Table 1 Test geometry.

Source height	500 mm
Bottom microphone height	200 mm
Top microphone height	500 mm
Horizontal separation source/receiver	1750 mm

6.5 Measurements

The test signal shall consist of broadband random or pseudo random noise.

Measure the heights along the normal to the surface of an average ground plane, see figure 2. When defining the ground plane exclude vegetation such as grass.

Note. It is especially important to measure the distances and heights accurately if the surface to be measured is hard (like asphalt or packed soil).

Figure 2 Geometry of source and receiver.

Direct the microphones towards the point on the ground below the source. Direct the source towards the point on the ground below the microphones. For a given geometry make at least 4 independent measurements. Measure, during at least 15 seconds, the time-averaged sound pressure level of each one third octave band within the frequency range of interest. Between each measurement series translate and/or rotate the source and the microphones to an adjacent piece of identical ground.

6.6 Criterion for background noise

For each frequency within the frequency range of interest the background noise shall be at least 15 dB below the level of the signal from the loudspeaker.

6.7 Evaluation of the measurement results

For each of n measurements, i, and each frequency band, j, calculate the level difference, ΔL_{ij}, between the top microphone and the bottom microphone. Then, for each frequency band, calculate the average value:

$$\Delta L_{Mj} = \frac{\sum_{i=1}^{n} \Delta L_{ij}}{n} \tag{6}$$

and the standard deviation of the level differences obtained in each set of n different measurements:

$$s_{Dj} = \sqrt{\frac{\sum_{i=1}^{n} \left(\Delta L_{Mj} - \Delta L_{i}\right)^2}{n-1}} \tag{7}$$

Use the average level differences to determine the flow resistivity class yielding the minimum error (difference to precalculated level differences) e described in annex A. In addition determine the error differences E-e of the different flow resistivity classes.

Use e and the maximum standard deviation to qualify the measurement according to 6.8, and the error differences E-e to state the results according to 7.

6.8 Qualification of the measurement series

If max(s_{Dj}) exceeds 4 dB the measurement is not valid according to this Nordtest method. The ground surface is then either too uneven or too inhomogeneous. If the minimum error e exceeds 15 dB the one-parameter impedance model is not valid. For further actions, see 6.9.

6.9 Measures to take in case of failure to qualify

If max(s_{Dj}) exceeds 4 dB try to repeat the measurements on a better test site.

If e exceeds 15 dB try to apply the modified one-parameter model. If the measurements still do not qualify the impedance cannot be evaluated with this Nordtest method. An alternative method is described in Annex D.

7 Statement of the results

The result shall be given as a flow resistivity class:

If all of the error differences E-e are greater than or equal to 4 dB, just state the flow resistivity class σ which gave the minimum error e.

If one or more flow resistivity classes lead to an error difference E-e of less than 4 dB, then state them within parenthesis after the flow resistivity class σ, e.g. flow resistivity class σ (σ_1,σ_2,...).

8 Information to be reported

a) State that the measurements have been carried out in full conformity with this Nordtest method. Any deviations shall be reported.

b) State the flow resistivity class(-es) according to clause 7, and, optionally, the specific normalised impedance as a function of frequency.

c) State the impedance model used

d) State $max(s_{Dj})$, e, and E-e for all classes where E-e < 4 dB.

e) Describe the character (roughness, vegetation, type of soil, thickness of layers) of the piece of ground measured.

f) If the modified one-parameter model was used, also indicate the reference depth from the tables.

g) Plot the mean level difference vs. frequency along with the reference curve which gives the best fit in a diagram.

Annex A Curve fitting (Normative)

A.1 Level difference

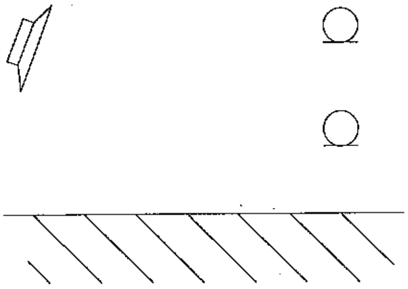

Figure A.1 Geometry of the measurement setup.

The level difference between the two points, top and bottom, for a given third octave frequency f, is given by

$$\Delta L = L_B - L_A \qquad \text{(A.1)}$$

where

L_B is the sound pressure level measured at the top position and

L_A is the sound pressure level measured at the bottom position

A.2 Determination of the best fit impedance

A.2.1 One parameter

The one-parameter model can be used to find the impedance from a two microphone measurement by using table B.1 (or B.2 if the temperature is low) to calculate the error. The flow resistivity which minimizes the error is used to calculate the impedance with equation (2).

The first step is to measure the level difference for the appropriate geometry. The measured average level difference values are denoted by $\Delta L_{M,j}$, where j is the number of the frequency band according to table A.1.

Table A.1 Third octave band nominal center frequencies.

J	1	2	3	4	5	6	7	8	9	10	11	12
Third-octave	200	250	315	400	500	630	800	1000	1250	1600	2000	2500

Now, for each flow resistivity class considered (see annex B), calculate the error defined by

$$E = \sum_{j=1}^{12} \left| \Delta L_{M,j} - \Delta L_{C,j} \right| \qquad \text{(A.2)}$$

where $\Delta L_{C,j}$ are the level difference values given in table B.1 or B.2 of annex B for the different flow resistivity classes. One flow resistivity class σ will yield the minimum error, e, and this is the resulting flow resistivity class, which now has to be qualified and stated in the report according to 6.7, 6.8 and 7.

A.2.1 Two parameters

In some situations, like snow covered ground, the one-parameter model may not yield any good results. Then an alternative approach is to use a two parameter model. That means we have to minimize the error with respect to two parameters, and then calculate the impedance from them. If one of the parameters can be measured, like the layer depth in the model below, we can use the same principle as for the one parameter model.

In the case of a soft layer on top of a hard ground, such as snow on frozen ground, use the model (4), via the tables B.3 - B.8 depending on layer depth and temperature. If the layer is thicker than 17.5 cm, use the one-parameter model. If not, use the table corresponding to the depth which is closest to the real value, and determine the best fit class with the method described for the one-parameter model. When presenting the result, also indicate measured layer depth, and the layer depth used in the comparisons.

Note. For very thin layers this method may not work. This will show as unacceptable errors in the calculations.

Annex B Level difference tables and flow resistivity classes (Normative)

B.1 The different flow resistivity classes

For the one-parameter impedance model the ground surface is divided into 12 flow resistivity classes as shown in table B.1. The classes are denoted *Flow resistivity class 10, Flow resistivity class 16*, etc. 10 indicates a flow resistivity of 10 kNs/m^4, 16 16 kNs/m^4, etc.

B.2 The one-parameter model

Table B.1. Pre-calculated level differences, $\Delta L_{C,j}$, for geometry A using the impedance model from eq. (2). High temperatures.

	Flow resistivity (σ) *10^3	c=340 m/s (5° - 30°C)										
f (Hz)	**10**	**16**	**25**	**40**	**63**	**100**	**160**	**250**	**400**	**630**	**2000**	**20000**
200	-1.3	-1.7	-1.8	-1.7	-1.6	-1.5	-1.4	-1.3	-1.3	-1.2	-1.2	-1.1
250	-0.9	-2.0	-2.4	-2.5	-2.4	-2.3	-2.1	-2.0	-1.9	-1.9	-1.8	-1.7
315	0.4	-1.4	-2.8	-3.6	-3.7	-3.6	-3.4	-3.2	-3.1	-3.0	-2.8	-2.7
400	2.3	0.7	-1.6	-3.9	-5.3	-5.8	-5.6	-5.4	-5.2	-5.0	-4.7	-4.5
500	3.7	3.1	1.7	-0.9	-4.1	-7.1	-9.0	-9.6	-9.5	-9.3	-8.7	-8.3
630	4.0	4.2	4.2	3.5	1.7	-1.1	-4.3	-7.1	-9.7	-11.7	-14.7	-16.0
800	3.0	3.7	4.4	5.3	5.9	5.5	3.9	2.0	0.2	-1.2	-3.4	-4.9
1000	0.6	1.5	2.5	4.0	5.6	7.5	9.0	9.1	8.1	6.8	4.7	3.3
1250	-3.2	-2.4	-1.3	0.1	1.8	4.0	6.6	9.3	12.0	13.5	12.4	10.4
1600	-3.3	-3.4	-3.6	-3.6	-3.4	-2.8	-1.6	0.2	2.5	4.8	10.1	15.0
2000	-0.7	-0.8	-0.9	-1.1	-1.3	-1.5	-1.8	-2.1	-2.4	-2.5	-2.5	-2.1
2500	-1.2	-1.2	-1.2	-1.2	-1.1	-0.9	-0.8	-0.6	-0.4	-0.2	0.3	0.7

Table B.2. Pre-calculated level differences, $\Delta L_{C,j}$, for geometry A using the impedance model from eq. (2). Low temperatures.

	Flow resistivity (σ) *10^3	c=325 m/s (-20° - +5°C)										
f (Hz)	**10**	**16**	**25**	**40**	**63**	**100**	**160**	**250**	**400**	**630**	**2000**	**20000**
200	-1.3	-1.8	-1.9	-1.9	-1.7	-1.6	-1.5	-1.4	-1.4	-1.3	-1.3	-1.2
250	-0.8	-1.9	-2.5	-2.7	-2.6	-2.5	-2.3	-2.2	-2.1	-2.0	-1.9	-1.9
315	0.7	-1.1	-2.8	-3.8	-4.0	-3.9	-3.7	-3.5	-3.4	-3.3	-3.1	-3.0
400	2.6	1.2	-1.0	-3.7	-5.5	-6.3	-6.3	-6.0	-5.8	-5.6	-5.2	-5.0
500	3.8	3.4	2.3	0.1	-3.1	-6.5	-9.2	-10.4	-10.7	-10.6	-10.0	-9.5
630	3.9	4.2	4.4	4.1	2.8	0.4	-2.5	-5.2	-7.6	-9.6	-12.8	-14.9
800	2.7	3.4	4.2	5.3	6.2	6.3	5.3	3.6	1.9	0.5	-1.6	-3.0
1000	0.0	0.8	1.9	3.4	5.1	7.2	9.2	10.0	9.4	8.3	6.1	4.6
1250	-3.8	-3.1	-2.2	-0.9	0.7	2.8	5.3	8.0	11.0	13.4	14.2	12.0
1600	-2.7	-2.9	-3.1	-3.4	-3.6	-3.6	-3.1	-2.0	-0.2	1.7	6.3	10.7
2000	-0.6	-0.6	-0.7	-0.7	-0.8	-1.0	-1.1	-1.2	-1.3	-1.3	-1.2	-0.9
2500	-0.7	-0.8	-1.0	-1.2	-1.4	-1.4	-1.4	-1.3	-1.1	-0.9	-0.5	0.0

B.3 The modified one-parameter model with soft top layer of known thickness

Table B.3. Pre-calculated level differences for geometry A using impedance model (4) with L=0.05. High temperatures.

	Flow resistivity (σ) *10^3	c=340 m/s (5° - 30°C)										L=0.05
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-2.8	-2.8	-2.6	-2.4	-2.0	-1.6	-1.4	-1.3	-1.3	-1.2	-1.2	-1.1
250	-4.9	-4.7	-4.4	-3.7	-2.9	-2.3	-2.1	-2.0	-1.9	-1.9	-1.8	-1.7
315	-10.6	-9.6	-7.7	-5.6	-4.2	-3.6	-3.3	-3.2	-3.1	-3.0	-2.8	-2.7
400	-0.2	-0.5	-2.1	-4.1	-5.2	-5.6	-5.6	-5.4	-5.2	-5.0	-4.7	-4.5
500	13.7	10.6	6.9	2.1	-2.6	-6.6	-9.0	-9.6	-9.5	-9.3	-8.7	-8.3
630	8.6	7.8	6.9	5.0	2.2	-1.2	-4.4	-7.1	-9.7	-11.7	-14.7	-16.0
800	4.9	4.6	4.6	4.8	5.3	5.2	3.9	2.0	0.2	-1.2	-3.4	-4.9
1000	0.3	0.5	1.4	3.0	5.3	7.5	9.0	9.1	8.1	6.8	4.7	3.3
1250	-6.3	-4.5	-2.4	-0.2	1.9	4.0	6.6	9.3	12.0	13.5	12.4	10.4
1600	-2.8	-2.8	-2.9	-3.2	-3.3	-2.8	-1.6	0.2	2.5	4.8	10.1	15.0
2000	-0.3	-0.6	-0.9	-1.1	-1.3	-1.5	-1.8	-2.1	-2.4	-2.5	-2.5	-2.1
2500	-0.2	-0.8	-1.1	-1.2	-1.1	-0.9	-0.8	-0.6	-0.4	-0.2	0.3	0.7

Table B.4. Pre-calculated level differences for geometry A using impedance model (4) with L=0.10. High temperatures.

	Flow resistivity (σ) *10^3	c=340 m/s (5° - 30°C)										L=0.10
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-4.2	-3.1	-2.2	-1.8	-1.6	-1.5	-1.4	-1.3	-1.3	-1.2	-1.2	-1.1
250	-3.9	-2.9	-2.5	-2.4	-2.4	-2.3	-2.1	-2.0	-1.9	-1.9	-1.8	-1.7
315	3.1	0.0	-2.2	-3.3	-3.6	-3.6	-3.4	-3.2	-3.1	-3.0	-2.8	-2.7
400	5.4	2.6	-0.6	-3.7	-5.3	-5.8	-5.6	-5.4	-5.2	-5.0	-4.7	-4.5
500	4.9	3.6	1.7	-1.0	-4.2	-7.1	-9.0	-9.6	-9.5	-9.3	-8.7	-8.3
630	3.6	3.6	3.7	3.3	1.7	-1.1	-4.3	-7.1	-9.7	-11.7	-14.7	-16.0
800	1.9	3.0	4.3	5.4	5.9	5.5	3.9	2.0	0.2	-1.2	-3.4	-4.9
1000	0.2	1.6	2.7	4.0	5.6	7.5	9.0	9.1	8.1	6.8	4.7	3.3
1250	-2.3	-2.1	-1.3	0.0	1.8	4.0	6.6	9.3	12.0	13.5	12.4	10.4
1600	-3.7	-3.6	-3.6	-3.6	-3.4	-2.8	-1.6	0.2	2.5	4.8	10.1	15.0
2000	-0.6	-0.7	-0.9	-1.1	-1.3	-1.5	-1.8	-2.1	-2.4	-2.5	-2.5	-2.1
2500	-1.0	-1.2	-1.2	-1.2	-1.1	-0.9	-0.8	-0.6	-0.4	-0.2	0.3	0.7

Table B.5. Pre-calculated level differences for geometry A using impedance model (4) with L=0.15. High temperatures.

	Flow resistivity (σ) *10^3		c=340 m/s (5° - 30°C)									L=0.15
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-1.8	-1.7	-1.7	-1.7	-1.6	-1.5	-1.4	-1.3	-1.3	-1.2	-1.2	-1.1
250	0.1	-1.5	-2.2	-2.5	-2.4	-2.3	-2.1	-2.0	-1.9	-1.9	-1.8	-1.7
315	1.8	-0.7	-2.6	-3.6	-3.7	-3.6	-3.4	-3.2	-3.1	-3.0	-2.8	-2.7
400	2.7	0.7	-1.7	-4.0	-5.3	-5.8	-5.6	-5.4	-5.2	-5.0	-4.7	-4.5
500	3.1	2.7	1.6	-0.9	-4.1	-7.1	-9.0	-9.6	-9.5	-9.3	-8.7	-8.3
630	3.5	4.1	4.3	3.5	1.7	-1.1	-4.3	-7.1	-9.7	-11.7	-14.7	-16.0
800	3.2	3.8	4.5	5.3	5.9	5.5	3.9	2.0	0.2	-1.2	-3.4	-4.9
1000	0.9	1.5	2.5	4.0	5.6	7.5	9.0	9.1	8.1	6.8	4.7	3.3
1250	-3.4	-2.4	-1.3	0.1	1.8	4.0	6.6	9.3	12.0	13.5	12.4	10.4
1600	-3.2	-3.4	-3.6	-3.6	-3.4	-2.8	-1.6	0.2	2.5	4.8	10.1	15.0
2000	-0.7	-0.8	-0.9	-1.1	-1.3	-1.5	-1.8	-2.1	-2.4	-2.5	-2.5	-2.1
2500	-1.2	-1.2	-1.2	-1.2	-1.1	-0.9	-0.8	-0.6	-0.4	-0.2	0.3	0.7

Table B.6. Pre-calculated level differences for geometry A using impedance model (4) with L=0.05. Low temperatures.

	Flow resistivity (σ) *10^3		c=325 m/s (-20° - +5°C)									L=0.05
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-3.0	-2.9	-2.8	-2.5	-2.1	-1.7	-1.5	-1.4	-1.4	-1.3	-1.3	-1.2
250	-5.3	-5.1	-4.7	-4.0	-3.1	-2.5	-2.3	-2.2	-2.1	-2.0	-1.9	-1.9
315	-12.1	-10.7	-8.4	-6.0	-4.5	-3.9	-3.6	-3.5	-3.4	-3.2	-3.1	-3.0
400	2.1	1.4	-0.8	-3.5	-5.3	-6.1	-6.2	-6.0	-5.8	-5.6	-5.2	-5.0
500	13.4	10.9	7.5	2.9	-1.9	-6.3	-9.3	-10.5	-10.7	-10.6	-10.0	-9.5
630	8.2	7.6	6.8	5.3	2.9	0.0	-2.9	-5.5	-7.8	-9.7	-12.9	-14.9
800	4.4	4.2	4.3	4.8	5.6	6.0	5.1	3.4	1.7	0.4	-1.7	-3.0
1000	-0.6	-0.3	0.7	2.6	5.0	7.4	9.3	10.0	9.3	8.2	6.0	4.6
1250	-6.8	-5.0	-3.0	-0.9	1.0	3.1	5.6	8.3	11.3	13.6	14.1	12.0
1600	-2.0	-2.2	-2.5	-3.1	-3.5	-3.6	-3.0	-1.8	-0.1	1.9	6.5	10.8
2000	-0.4	-0.5	-0.7	-0.8	-0.9	-1.0	-1.1	-1.2	-1.3	-1.3	-1.2	-0.9
2500	0.4	-0.6	-1.1	-1.3	-1.4	-1.4	-1.4	-1.3	-1.1	-0.9	-0.5	0.0

Table B.7. Pre-calculated level differences for geometry A using impedance model (4) with L=0.10. Low temperatures.

	Flow resistivity (σ) *10^3		c=325 m/s (-20° - +5°C)									L=0.10
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-4.5	-3.3	-2.3	-1.9	-1.7	-1.6	-1.5	-1.4	-1.4	-1.3	-1.3	-1.2
250	-3.6	-2.9	-2.7	-2.6	-2.5	-2.4	-2.3	-2.2	-2.1	-2.0	-1.9	-1.9
315	3.7	0.3	-2.1	-3.5	-3.9	-3.9	-3.7	-3.5	-3.4	-3.2	-3.1	-3.0
400	5.6	2.9	-0.3	-3.6	-5.7	-6.3	-6.3	-6.0	-5.8	-5.6	-5.2	-5.0
500	4.9	3.7	2.1	-0.4	-3.5	-6.8	-9.3	-10.5	-10.7	-10.6	-10.0	-9.5
630	3.4	3.6	3.9	3.9	2.6	0.1	-2.8	-5.5	-7.8	-9.7	-12.9	-14.9
800	1.6	2.9	4.2	5.4	6.3	6.3	5.1	3.4	1.7	0.4	-1.7	-3.0
1000	-0.3	1.1	2.2	3.6	5.3	7.4	9.3	10.0	9.3	8.2	6.0	4.6
1250	-2.9	-2.8	-2.1	-0.8	0.9	3.0	5.6	8.3	11.3	13.6	14.1	12.0
1600	-3.0	-3.0	-3.1	-3.4	-3.6	-3.5	-3.0	-1.8	-0.1	1.9	6.5	10.8
2000	-0.5	-0.6	-0.7	-0.7	-0.8	-1.0	-1.1	-1.2	-1.3	-1.3	-1.2	-0.9
2500	-0.5	-0.8	-1.1	-1.2	-1.4	-1.4	-1.4	-1.3	-1.1	-0.9	-0.5	0.0

Table B.8. Pre-calculated level differences for geometry A using impedance model (4) with L=0.15. Low temperatures.

	Flow resistivity (σ) *10^3		c=325 m/s (-20° - +5°C)									L=0.15
f (Hz)	10	16	25	40	63	100	160	250	400	630	2000	20000
200	-1.8	-1.8	-1.8	-1.8	-1.7	-1.6	-1.5	-1.4	-1.4	-1.3	-1.3	-1.2
250	0.3	-1.5	-2.4	-2.7	-2.6	-2.4	-2.3	-2.2	-2.1	-2.0	-1.9	-1.9
315	2.0	-0.6	-2.7	-3.8	-4.0	-3.9	-3.7	-3.5	-3.4	-3.2	-3.1	-3.0
400	2.9	0.9	-1.4	-4.0	-5.7	-6.3	-6.3	-6.0	-5.8	-5.6	-5.2	-5.0
500	3.2	2.9	2.0	-0.2	-3.4	-6.8	-9.3	-10.5	-10.7	-10.6	-10.0	-9.5
630	3.4	4.2	4.5	4.1	2.6	0.1	-2.8	-5.5	-7.8	-9.7	-12.9	-14.9
800	2.9	3.6	4.3	5.4	6.2	6.3	5.1	3.4	1.7	0.4	-1.7	-3.0
1000	0.2	0.9	2.0	3.5	5.3	7.4	9.3	10.0	9.3	8.2	6.0	4.6
1250	-3.9	-3.1	-2.1	-0.8	0.9	3.0	5.6	8.3	11.3	13.6	14.1	12.0
1600	-2.6	-2.9	-3.1	-3.4	-3.6	-3.5	-3.0	-1.8	-0.1	1.9	6.5	10.8
2000	-0.6	-0.6	-0.7	-0.7	-0.8	-1.0	-1.1	-1.2	-1.3	-1.3	-1.2	-0.9
2500	-0.7	-0.9	-1.0	-1.2	-1.4	-1.4	-1.4	-1.3	-1.1	-0.9	-0.5	0.0

Annex C Demonstration of the method (informative)

Four measurements on rough grass land gave the following level differences:

Table C.1 Measured level differences

f	1	2	3	4	Average	Std dev
200	-1.4	-1.2	-1.3	-1.2	-1.28	0.10
250	-1.9	-1.8	-1.8	-1.8	-1.83	0.05
315	-3.1	-2.9	-3.1	-2.9	-3.00	0.12
400	-5.5	-5.2	-5.3	-5.3	-5.33	0.13
500	-10.1	-9.5	-10.4	-10.4	-10.10	0.42
630	-10.6	-11.2	-10.1	-11.3	-10.80	0.56
800	0.4	0.4	0.5	-1.3	0.00	0.87
1000	9.1	8.6	9.2	6.7	8.40	1.16
1250	13.4	13.5	14.8	13.1	13.70	0.75
1600	0.7	3	-0.6	2.8	1.48	1.73
2000	-3	-4.5	-4.1	-3.5	-3.78	0.66
2500	-1.2	-0.7	-0.6	-1.4	-0.97	0.39

As all the standard deviations are lower than 4 dB, the measurement is valid. The measurement were made at a temperature of +18 °C, so table B1 should be used to calculate the errors for the different flow resistivity classes:

Table C.2 Calculated errors E

Flow resistivity class	10	16	25	40	63	100	160	250	400	630	2000	20000
Error E	68.8	64.8	59.3	51.9	42.5	32.2	21.7	12.5	5.0	7.1	19.2	28.6

From these errors we get *e*=5.0 dB, which is less than 15 dB. We know that the result is flow resistivity class 400, but we need to calculate the error differences *E-e* in order to state the result correctly:

Table C.3 Error difference E-e

Flow resistivity class	10	16	25	40	63	100	160	250	400	630	2000	20000
E-e	63.8	59.8	54.3	46.9	37.5	27.2	16.7	7.5	0.0	2.1	14.2	23.6

Here we see that for class 630 *E-e* is less than 4 dB (and for 400 of course), so the correct statement of the measurement is:

The measured flow resistivity class according to this Nordtest method is: 400 (630)
The minimum error e is 5 dB, and the error difference for the 630 class is 2.1 dB.

If we want to state this as the normalized ground impedance, we use formula (3) with σ=400 000:

Table C.4
Real and imaginary part of normalized specific impedance, calculated for flow resistivity class 400

f	Re(Z)	Im(Z)
200	16.0	19.8
250	13.6	16.8
315	11.6	14.2
400	9.9	11.9
500	8.5	10.1
630	7.3	8.6
800	6.3	7.2
1000	5.5	6.1
1250	4.8	5.2
1600	4.1	4.3
2000	3.7	3.7
2500	3.2	3.1

And finally the plot of the mean level difference and the reference curve from table B.1:

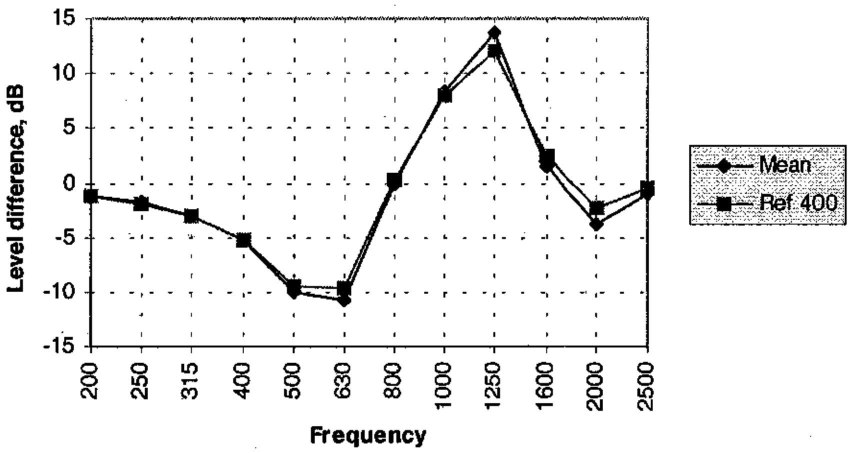

Figure C.1 Mean (measured) and reference level difference for the best fit impedance class, 400.

Annex D Variable porosity surfaces (informative)

Some surfaces cannot be described by the one parameter model, or the modified one-parameter model without leading to too large errors in the Nordtest method. In such cases other impedance models can be used. Such models have not been included in the Nordtest method because of the difficulty in coupling them to the flow resistivity classes and to make tables simple enough. In the following some guidelines will be given on how apply a different impedance model.

If the flow resistivity is rather high and the porosity changes with depth, the following model gives a better description: (other suitable models may be found in literature for other cases)

$$Z = 0.484(1+i)\sqrt{\frac{\sigma_e}{f}} + 30i\frac{\alpha_e}{f}$$

Note that the flow resistivity σ_e is not the same parameter as in the previously presented models.

To calculate the level difference for any impedance model, use the following method:

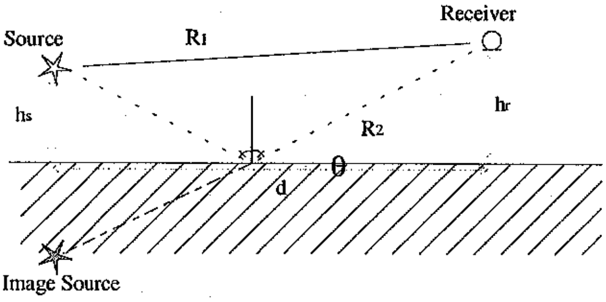

Figure D.1
Source and receiver above an impedance plane.

1) For both receivers, calculate the sound pressure in each frequency band using the following formulas: (Δf_r=0.116)

$$L_p = 10\ \log\left(1 + \left[\frac{R_1}{R_2}\right]^2 |Q|^2 + \frac{2R_1}{R_2}|Q|\frac{\sin[k(R_2 - R_1)\Delta f_r]}{k(R_2 - R_1)\Delta f_r}\cos[k(R_2 - R_1) + \varphi]\right) - 20\log(R_1)$$

$$R(\theta) = \frac{\cos(\theta) - Z^{-1}}{\cos(\theta) + Z^{-1}}$$

$$Q = |Q|e^{i\varphi} = R(\theta) + [1 - R(\theta)]E(\rho)$$

$$E(\rho) = 1 + i\sqrt{\pi}\rho e^{-\rho^2} erfc(-i\rho)$$

$$\rho = \frac{1+i}{2}\sqrt{kR_2}(Z^{-1} + \cos(\theta))$$

$$erfc(x) = 1 - erf(x) = \frac{2}{\pi^{1/2}}\int_x^\infty e^{-t^2}dt$$

2) Calculate the level difference

$\Delta L_C = L_B - L_A$

L_B is the sound pressure level calculated at the top position and

L_A is the sound pressure level calculated the bottom position

3) The combination of the two parameters that gives the smallest error (A.2) is the result

Annex E Some measured flow resistivity classes (informative)

A number of measurements are presented in table E.1. They have been carried out in accordance with the proposed method by SP, SINTEF and DELTA.

Table E.1 Results of measurements carried out by SP, SINTEF and DELTA with the proposed method.

Description	Flow res. Class kNs/m^4
Soft forest floor with blueberry greens and moss	**40**
Short grass, green moss and blueberry greens	**40**
Forest floor covered by weeds	**63 (100)**
Earth and bark, sparse vegetation	**100**
Dense shrubbery, 20 cm high	**100**
Rough grassland	**100**
Peat or turf area, homogeneous organic material	**100**
Soft forest floor covered with pine needles	**160**
Agricultural field	**160 (250)**
Earth covered with leaves and twigs	**160 (250)**
Lawn, moderately stepped on	**160 (250)**
Pasture	**250 (160)**
Lawn, seldom stepped on	**250**
Earth mixed with sawdust	**250**
Lawn	**250 (400)**
Gravel, earth and sparse grass	**630**
Relatively dense soil sparsely covered by grass and other low greens.	**630**
Grass, soccer field	**630 (2000)**
Mixed paving stones and grass	**630 (2000)**
Gravel parking lot	**2000 (630)**
Hard soil	**2000 (630)**
Sandy forest floor	**2000 (630)**
Gravel road, small stones	**2000**
Gravel road, stones and dust	**2000**
Old gravel field with sparse vegetation	**2000 (20 000)**

Annex F Example of sound propagation calculations (informative)

Assume that we have a point source located 30 m from the receiver, 0.2 m above the ground. The listener is 1.5 m above ground level. What effect will different ground types have on the perceived sound pressure? The measurements in annex E indicate that a soft forest floor has flow resistivity class 40, a harder 160 and a grass field 630. If we assume that the impedance model (3) is valid outside of the measured frequency region, we can use the theory of the spherical reflection coefficient to calculate the effect, see figure F.1.

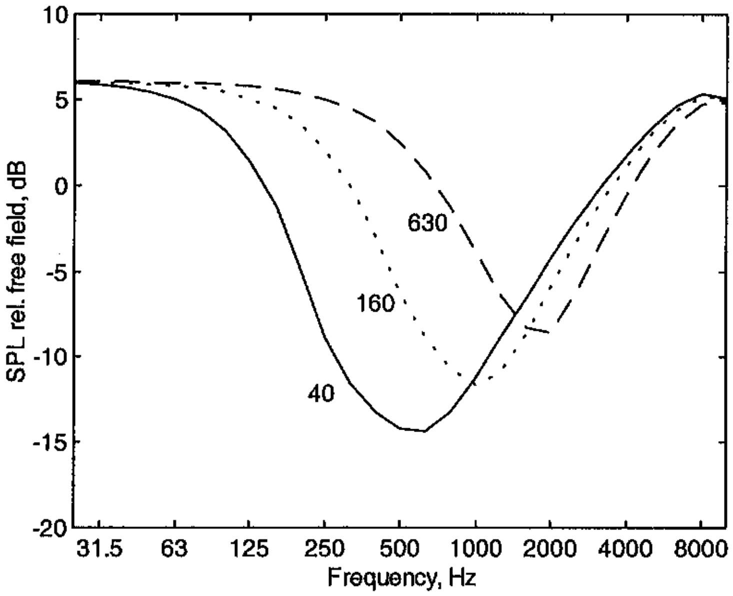

Figure F.1
Sound pressure level relative free field for three flow resistivity classes, 40, 160 and 630.

Calculated using spherical reflection coefficient, hs=0.2, hr=1.5, d=30 m

If we assume that the source emits a typical road traffic spectra (ISO, 50 km/h) we can calculate the difference in A-weighted sound pressure level, see table F.1

Table F.1 Calculated SPL, normalized to 50 dB for the flow resistivity class 40

Flow resistivity class	40	160	630
SPL dB, A-weight	**50**	**52.1**	**55.1**