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# Ground Characterisation from Short Range Propagation Measurements

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## Introduction

In recent years most work on short range measurements of excess attenuation has concentrated on characterising the acoustical ground properties in terms of one parameter, the effective flow resistivity ($\sigma_e$), using a simple a semi-empirical relationship developed by Delany and Bazley [1]. Many authors have used this model to compare predicted and measured impedance and excess attenuation over various ground surfaces [2] [3]. In general however the use of this model has met with limited success. It has been found that the measured values of flow resistivity ($\sigma$) for grass, bare sandy soil, cultivated farm land and hard clay and forest floor exceeded the best fit effective flow resistivity values ($\sigma_e$) needed to fit impedance data, by a factor of roughly two [4] [5]. This may be expected due to the differing values in porosity between fibreglass samples ($\Omega = 1.0$) on which the semi-empirical formulae are based and soils ($\Omega \approx 0.4$). However other measurements made over a grass field [6] show the reverse situation. The measured values of flow resistivity were considerably less than the values of $\sigma_e$ predicted using an impulse technique. There are several alternatives to this single parameter model [7] [8] [9]. In this paper more sophisticated ground impedance models and their various approximations [7] [2] are used to characterise non-grassland and snow properties in a more realistic manner than that resulting from use of the one parameter semi-empirical model.

## Theory

The theory assumes a rigid frame, with propagation of a sound wave below the ground surface only occurring within the air-filled pores. The validity of modelling the frame of the soil or snow as rigid has been demonstrated [10] [11]. An assumption is also made that soils are locally reacting [3]. The theory used for sound propagation from a point source is based upon the Weyl van der Pol equation, which has been shown to be an adequate approximation above a locally reacting surface and for ranges greater than a wavelength. In these calculations snow is allowed to be externally reacting and the method for calculating propagation from a point source is based on an approximate form for an externally reacting half-space [12] [13]. The difference in pressure between two vertically separated microphones is equal to total field at the top microphone minus the total field at the bottom microphone. In the level difference measurement ideally the lower microphone should be on the ground, so that there is no path length difference between the direct and reflected sound waves reaching the microphone and its contribution can be considered as equivalent to the direct ray. However microclimatic conditions are likely to involve steepest sound velocity gradients near the ground [14], and the lower microphone was therefore usually located a few centimetres above the ground surface. In addition the propagation range had to be sufficiently short to enable study of a relatively small area of soil, and reduce the influence of meterological conditions. An example of a dip and peak interference pattern, level difference spectrum is shown in Figure 1. Curves like this exhibiting peaks and troughs can be compared with predictions from acoustical models using a least sum of squares algorithm to obtain predicted ground parameter values.

## IMPEDANCE MODELS

Delany and Bazley [1] describe a method of relating acoustic impedance to a single parameter the airflow resistivity of fibreglass absorbents. Empirical relationships between normalised surface impedance $Z_c$ and an effective flow resistivity $\sigma_e$ can be expressed as

$$Z_c = 1 + 0.05\left[\frac{f}{\sigma_e}\right]^{-0.75} + i0.077\left[\frac{f}{\sigma_e}\right]^{-0.73} \tag{1}$$

where f is the frequency in Hz. Since the porosity for the fibrous materials under investigation was $\approx 1$, the authors were able to replace the effective flow resistivity $\sigma_e$ by the actual value $\sigma$.

Attenborough [7] [2] has developed an impedance model based on theoretical analysis of the acoustic behaviour of rigid homogeneous, porous, granular materials. A four parameter model can be approximated to a model involving three parameters where

$$Z_c \approx \frac{1}{k_b}\left[\frac{4}{3}\left[\frac{T}{\Omega}\right] + i\frac{2\sigma_{pe}}{\pi\rho_o f}\right]\left(\frac{2\pi f}{c_o}\right) \tag{2}$$

where the propagation constant in the soil is

$$k_b \approx \sqrt{\gamma}\left[\left(\frac{4}{3} - \frac{\gamma-1}{\gamma}N_{pr}\right)T + i\frac{2\sigma_{pe}}{\pi\rho_o f}\right]^{0.5}\left(\frac{2\pi f}{c_o}\right) \tag{3}$$

and where $\sigma_{pe}= sp^2\sigma\Omega$ an effective flow resistivity ($sp^2$ is a pore shape factor), T is the tortuosity, $\Omega$ the porosity, $\rho_o$ is the density of air, $c_o$ is the speed of sound in air, $N_{pr}$ is the Prandtl number in air and $\gamma$ is the ratio of specific heats.

A more severe approximation of Equation 2 is a one parameter approximation [7] which expresses impedance in terms of an effective flow resistivity $\sigma_e = sp^2\sigma/\Omega = \sigma_{pe}/\Omega^2$. This very low frequency/very high flow resistivity approximation may be written

$$Z_c = 0.436\left(\frac{\sigma_e}{f}\right)^{0.5}(1+i) \tag{4}$$

This approximation has equal real and imaginary parts and, the bulk propagation constant $k_b$ can be written as

$$a\,\mathrm{or}\,b = 0.0112(\Omega^2\sigma_e)^{0.5}\sqrt{f}(1+i) \tag{5}$$

which includes the additional parameter of porosity $\Omega$. The approximations of impedance using equations 4 and 5 were used in equation 6 for simplicity in modelling a layered soil. According to the formulae presented by [15] the impedance of a two layered fluid is given by

$$Z_s = Z_1\left(\frac{Z_2 - iZ_1\tan(k_b d)}{Z_1 - iZ_2\tan(k_b d)}\right) \tag{6}$$

where $Z_1$ is the normalised characteristic impedance of the upper porous layer, $Z_2$ is the normalised characteristic impedance of the lower porous half-space $k_b$ is the bulk propagation constant in the upper layer and $d$ is the depth of the upper layer. Using the approximations equations 4 and 5 each layer was characterised by an effective flow resistivity $\sigma_e$ and porosity $\Omega$, together with a depth, d,of the upper layer. For a low flow resistivity medium like snow the three parameter low frequency/high flow resistivity approximation proves adequate up to 1KHz [2]. In general for level difference data analysis above this frequency high frequency/low flow resistivity approximations should be used [16]. However since level difference measurements were only measured between 100-1000Hz the high frequency/low flow resistivity approximations were not used.

## EXPERIMENT DESIGN AND MEASUREMENT

Measurements of the short range level difference between two vertically separated microphones [2], were made over various well-defined ground types including sands, silts, clay and snow. Experimental sites were selected where the upper few centimetres of the soil could be expected to be homogeneous or possess a distinct layered structure. In addition sites with distinct agricultural wheeling and soil compaction treatments were also studied. The measurement geometry ranges varied form 0.8m to 2m. The lower microphone was no higher than 0.1m and the upper microphone no higher than 0.5m. The source height was between 0.2 and 0.5m. The signal from a white noise source was passed through a low pass filter, amplified and broadcast through a 40 watt Tanoy PD40 drive unit with a 30cm long brass tube attached to the front. This acted as a point noise source. The recording system involved two microphones connected via preamplifiers and a microphone power supply to a dual channel FFT analyser. White noise was broadcast for 30 seconds duration, approximately the time it took the FFT analyser to average 128 spectra. The data was stored as the magnitude of the transfer function in dB on floppy disc and later transferred to a VAX main frame for analysis.

Independent non-acoustical measurements of porosity are made for every ground type and for the sands and soils, flow resistivity measurements are made also. The majority of flow resistivity measurements on soils were made using a compressed air flow rig or a Leonards apparatus [2].

## DEDUCTION OF GROUND PARAMETERS FROM ACOUSTIC MEASUREMENTS

The process of deducing ground parameters involved comparing measured level difference with theoretical predictions of the models. This procedure utilises a Nag library curve fitting routine (EO4JAF) and the calculation of a root mean least sum of squares (rms) between the predicted curve and the measured level difference spectrum, called the rms error. This error indicates the goodness of fit, the lower the value the closer the measured and predicted spectra lie.

A problem with fitting the three parameter approximation is non-uniqueness. For any one geometry configuration there could be two different combinations of effective flow resistivity $\sigma_{pe}$, tortuosity T and porosity $\Omega$ giving the same rms value. To overcome this, two or three different geometries, over the same area of soil, were fitted. A similar combination of parameters predicted for all geometries was regarded as the global minimum solution and the most probable combination of $\sigma_{pe}$, T and $\Omega$.

For the multi-layer model the fitting procedure was less precise as there was no routine available for iterating the five parameters (flow resistivity and porosity for each layer and the depth of the upper layer) required by this model. In this case some parameters were set to conventionally measured or assumed values. These usually included a measured porosity for both layers, a flow resistivity for the lower layer and the depth of the layer. All such measured or assumed values are indicated in brackets in the following tables, whilst those acoustically determined have no brackets. With four parameters out of the required five estimated, an iterative procedure was developed to estimate $\sigma_e$ for the upper layer until the smallest rms error was achieved. For some sites only three parameters were known and both the effective flow resistivity and porosity for the top layer had to be deduced using this iterative procedure.

## RESULTS AND DISCUSSION

Figures 1 and 2 show that best fit predictions of short range propagation above a homogeneous silt soil and a snow surface using the Delany and Bazley semi-empirical relationship for impedance are relatively poor. The rms errors resulting from fitting for both the three parameter approximation and the Delany and Bazley semi-empirical relationship on all surfaces studied are summarised in Table 1. Higher values of rms error result from fits that use the one parameter semi-empirical model than those obtained with the three parameter approximation. From this it can be concluded that the Delany and Bazley semi-empirical relationship (equation 1) is not as accurate as the three parameter approximation (equation 2) for characterising homogeneous outdoor ground surfaces. Moreover the latter predicts more information on soil properties.

Table 2 compares porosities determined acoustically through use of the three parameter approximation to measured air porosity values for some of the different soil types studied. Percentage errors of prediction are also presented. For soils, whether sand, clay or silt based acoustically determined air porosities tend to be higher than measured porosity values. This is probably because the acoustic reflection occurs at a shallower depth than the core sampling technique, particularly at higher frequencies, hence it is sampling that region of the soil profile with little overburden and possibly a lower bulk density. Those % errors which are negative indicate an acoustically deduced porosity which is less than the measured porosity. For the snow the acoustic reflection technique is likely to sample to a deeper depth than the conventional sampling technique, because of snow being generally more porous than soil. This is indeed the case at Site B shown in Table 2 where the error between the predicted and measured porosities 15% at 0-5cm decreases to 0% if an average measured porosity over a deeper depth 0-15cm is compared that predicted acoustically. On soils, where the predicted value of porosity is close to the measured value it may be inferred that the soil is homogeneous at least to the depth of the core sample.

The presence of a surface crust was usually obvious whilst experiments were being undertaken. This observation suggested the need for a layered model in fitting the level difference spectra. From the fitting of this model it is possible to determine the porosity $\Omega$ and an effective flow resistivity, $\sigma_e$ of both the crust and the soil beneath, as well as being able to estimate the crust depth. Table 3 shows all predicted and measured porosities for soil surfaces where crusts were known to occur. Assumed values are shown in brackets. Included here also are the wet Sandy Loam predictions. Porosity comparisons can be made between the upper and lower layers. In the fitting procedure for layer situations either the upper or lower layer porosity, in some cases both, were set equal to the average, or within the range, of measured porosities, (Indicated by brackets in Table 3). This accounts for the apparent zero or very low error values between acoustically determined porosity and measured air porosity values. Although these assumptions were made, the rms values for the layer fittings are low and in most cases with a layered soil it was impossible to resolve a good fit using an homogeneous model.

It is clear the surface crusts have a lower air porosity than the soil beneath. The data also indicates that both silt treatments experienced surface crusting but the poor practise site was more severly affected having a lower porosity. Field notes show that this was indeed the case. Furthermore, Hillel [17] suggests that soils become increasingly prone to crusting as their initial average aggregate size is reduced. Therefore it was to be expected that a poorly managed site with a somewhat worse soil structure was likely to be prone to more severe crust formation.

## CONCLUSIONS

The Delany and Bazley semi-empirical one parameter model can not be used alone to determine soil parameters, even with a priori knowledge of either air porosity or flow resistivity since the acoustically deduced effective flow resistivity can not be used to give sensible results. Over cultivated soils the semi-empirical model has been found consistently to give the effective flow resistivities higher than measured values. Thus implying porosities greater than unity. The three parameter approximation systematically gives a lower rms error when fitting short range propagation data obtained over all homogeneous surfaces studied compared to Delany and Bazley, indicating its superiority. A lower rms error is also obtained when fitting, assuming external reaction, snow data. The short range level difference technique enables deduction of air-filled porosity to within 10% of conventionally determined values on homogeneous soils. Other measurements were fitted using a layer model which incorporated a high flow resistivity layer above a low flow resistivity substrate. This has been found appropriate to some extent to determine the physical parameters and layer depths of surface crusts and saturated surface layers, without invasive sampling. Since similar values of effective flow resistivity and tortuosity have been found for both conditions it is clear that the acoustical technique does not discriminate between a dry, physically hard crust like that on the silt and the very wet surface layer on the sandy loam. Only visual observation of the physical conditions at the time of experimentation indicates the difference. More work needs to be done to study the effects of wetting and drying of soils on sound propagation through and near to their surfaces.

## *REFERENCES*

[1] Delany M.E. and Bazley E.N. *Applied Acoustics*, 3:309–322, 1970.

[2] Hess H.M. PhD thesis, Open Universtiy, Milton Keynes, UK., May 1988.

[3] Embleton T.F.W. and Piercy J.E.and Daigle G.A. *J. Acoust. Soc. Am.*, 74(4):1239–1244, 1983.

[4] Martens M.J.M., Van der Heijden L.A.M., Wathus H.H., and Van Rems W.J.J.M. *J. Acoust. Soc. Am.*, 78(3):970–980, Sept. 1985.

[5] Bolen L.N. and Bass H.E. *J. Acoust. Soc. Am.*, 69(4):950–954, April 1981.

[6] Don C.J. and Cramond A. *J. Acoust. Soc. Am.*, 77(4):1601, 1985.

[7] Attenborough K. *J. Acoust. Soc. Am.*, 73:785–799, 1983.

[8] Wempen J. In *Proc. I.O.A.*, 1987.

[9] S-I. Thomasson. *J. Acoust. Soc. Am.*, 61:659–674, 1977.

[10] Sabatier J.M., Bass H.E., Bolen L.M., Attenborough K., and V.V.S.S. Sastry. *J. Acoust. Soc. Am.*, 79(5):1345–1352, May 1986.

[11] S.M. Lee and J.C. Rogers. *J. Sound & Vib.*, 99(2):247–266, 1985.

[12] Attenborough K., Hayek S.I., and Lawther J.M. *J. Acoust. Soc. Am.*, 68:1493–1501, 1980.

[13] Quartarao L.R. Master's thesis, Pennsylvania State University, 1983.

[14] Huisman W.H.T., Martens M.J.M., and van Asseldonk W. *Proc. Inst. of Acous.*, 9, 1987.

[15] Brekhovskikh L.M. *Waves in Layered Media.* Academic Press, 1960.

[16] Attenborough K. and Buser O. *J. Sd & Vib.*, 124(1), 1988.

[17] Hillel D. In *Proc. of Transaction of 7th International Congress of Soil Science*, pages 330–339, Madison. Wisc. USA, 1960.

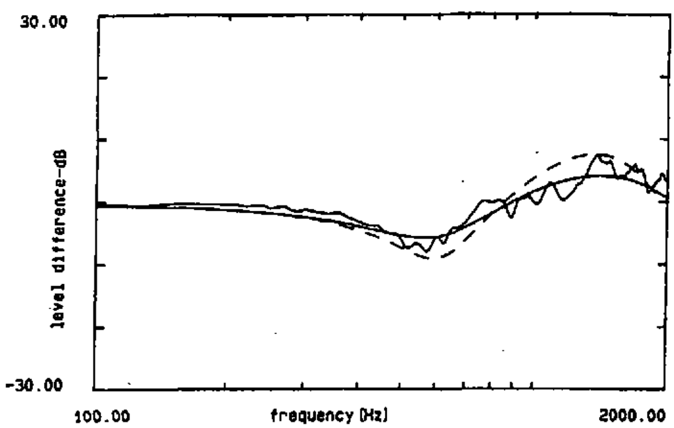


Figure 1: Example of Measured and Best Fit Level Difference over Silt A, Three Parameter Approximation (solid line)$\sigma_{pe}$ =8590, T=2.81, Ω=0.54, rms=1.61, Delany and Bazley (dashed line) $\sigma_e$ =130000, rms=6.50, geometry hs=0.45m,r=1.75m,hrt=0.45m,hrb=0.1m.

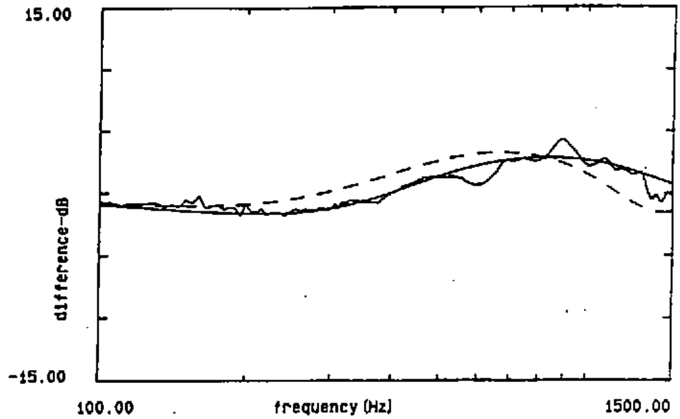


Figure 2: Example of Measured and Best Fit Level Difference over Snow, Three Parameter Approximation (solid line) $\sigma_{pe}$ =3814, T=2.83, $\Omega$=0.92, rms=0.72, Delany and Bazley (dashed line) $\sigma_e$ =4400, rms=4.35, geometry hs=0.5m,r=1.93m,hrt=0.5m,hrb=0.1m.

Table 1: Best Fit Ground Parameters for Various Soils

| | 3 para approx | | | | Delany and Bazley | |
|---|---|---|---|---|---|---|
| | $\sigma_{pe}$ | T | $\Omega$ | rms | $\sigma_e$ | rms |
| Sand 1 | 42000 | 2.15 | 0.36 | 1.88 | 906000 | 7.42 |
| Sand 2 | 19058 | 1.27 | 0.48 | 1.84 | 253000 | 4.54 |
| Sandy Loam dry | 24050 | 3.32 | 0.52 | 2.00 | 370000 | 10.95 |
| Sandy loam moist | 9380 | 1.23 | 0.39 | 1.56 | 218000 | 7.25 |
| Clay 1 wheeled | 14085 | 3.87 | 0.53 | 1.08 | 168000 | 2.29 |
| Clay 1 unwheeled | 12070 | 1.94 | 0.57 | 1.58 | 106000 | 2.75 |
| Clay 2 wheeled | 3680 | 2.68 | 0.42 | 1.43 | 112700 | 6.34 |
| Clay 2 unwheeled | 6280 | 3.35 | 0.57 | 1.76 | 91500 | 6.28 |
| Silt A Day 1 loose | 8670 | 2.89 | 0.56 | 1.29 | 110000 | 4.40 |
| Silt A Day 2 loose | 6040 | 2.24 | 0.49 | 1.23 | 106000 | 2.29 |
| Silt A Day 2 compacted | 14260 | 2.41 | 0.18 | 1.23 | 1045000 | 4.27 |
| Snow Site A | 3470 | 2.70 | 0.88 | 0.68 | 2500 | 2.50 |
| Snow Site B | 1420 | 1.11 | 0.60 | 0.90 | 7500 | 2.50 |

Table 2: Comparison of Acoustically Deduced and Measured Air Porosity for all Soil Types

| Surface | Treatment | Pred.Ω | Meas.Ω | % Error | Av.sample Depth cm |
|---|---|---|---|---|---|
| Sand 1 | | 0.36 | 0.35 | 3 | 0 - 3 |
| Sand 2 | | 0.48 | 0.47 | 2 | 0 - 3 |
| Sandy | dry | 0.52 | 0.49 | 6 | 0 - 5 |
| Loam | moist | 0.39 | 0.33 | 18 | 0 - 5 |
| Clay | unwheeled | 0.57 | 0.55† | | |
| (day1) | wheeled | 0.53 | 0.62† | | |
| Clay | unwheeled | 0.57 | 0.55 | 4 | 0 - 3 |
| (day2) | wheeled | 0.42 | 0.47 | -11 | 0 - 3 |
| Silt A | cultivated | 0.56 | 0.54 | 4 | 0 - 3 |
| (day1) | | | | | |
| Silt A | cultivated | 0.49 | 0.66† | | |
| (day2) | compacted | 0.18 | 0.23 | -22 | 0 - 3 |
| Silt A | cultivated | 0.47 | 0.53 | -11 | 0 - 6 |
| (day3) | | | | | |
| Snow A | | 0.88 | 0.76 | 16 | 0-5 |
| | | 0.88 | 0.73 | 20 | 0-15* |
| Snow B | | 0.60 | 0.52 | 15 | 0-5 |
| | | 0.60 | 0.60 | 0 | 0-15* |

† possible core sampling error

* increased sampling depth

Table 3: Deduced Ground Parameters for Various Layered Soils

| Soil | Feature | Layer | Pred.Ω | Meas.Ω | %error | rms | sample depth |
|---|---|---|---|---|---|---|---|
| Sand 3 | crusted | t | (0.13) | 0.14 | -7 | 1.73 | 0 - 1 |
| | | b | (0.31) | 0.27 | 15 | " | 1 - 5 |
| Silt A | | | | | | | |
| | compacted | t | 0.23 | - | | 2.59 | |
| | | b | (0.32) | 0.32 | 0 | " | 0 - 3 |
| Silt B | cultivated | t | 0.15 | - | | 3.01 | |
| | wheeling | b | (0.48) | 0.48 | 0 | " | 0 - 3 |
| Silt B | poor | t | 0.12 | - | | 3.89 | |
| | practise | b | (0.40) | 0.44 | -9 | " | 0 - 3 |
| Sandy | wet | t | (0.11) | 0.11 | 0 | 2.92 | 0 - 1 |
| loam | | b | (0.39) | 0.27 | 39 | " | 0 - 5 |