GROUND CHARACTERIZATION FOR JAPE*

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SUMMARY

Above-ground propagation modelling at the JAPE site requires a reasonably accurate model for the acoustical properties of the ground. Various models for the JAPE site are offered based on theoretical fits to short range data and to longer range data obtained with random noise and pure tones respectively from a loudspeaker under approximately quiescent isothermal conditions.

INTRODUCTION AND THEORY

A common feature of propagation models that takes into account various meteorological influences on sound propagating near to the ground is that they must also take account of the acoustical properties of the ground. Where direct impedance measurements are not available, advantage must be taken of indirect methods. Short range propagation measurements have been advocated often as one basis for indirect ground characterization (refs. 1 and 2).

A short range measurement of the level difference spectrum between vertically-separated microphones at 0.1 and 1 m height and 1.75 m from a source at height 0.45 m, has been made at three positions (8, 24 and 27) on the JAPE site (ref. 3). Probe (buried) microphone measurements have been made also at short range. However these latter data were not available at the OU at the time of preparing this paper. Measurements that were made available to the OU included data from loudspeaker sources broadcasting pure tones at position 5 (2 m height on North tower), geophone receivers (channels 20 and 21 directly below microphones) and microphone receivers at 0 m and 1 m above ground at a range of 100 m, 200 m, 300 m, 400 m and 500 m from the source during meteorological conditions that indicated good mixing and the absence of any significant sound speed gradients. In this report we concentrate on the received level difference spectrum between microphones corresponding to channels 14 and 15 at a range of 500 m from the source.

The averaged level difference data at both short range (1.75 m) and longer range (500 m) have been analysed by (a) computing level difference spectra with assumed impedance values, (b) comparing computed spectra with measured ones and (c) proceeding until the best agreement was

* Work sponsored in part by the U.S. Army through its European Research Office.

achieved. This process requires use of an impedance model to provide some constraint on the frequency dependence of the impedance. Several such models have been considered in the literature (ref. 4). Three of these models are considered here:

(1) Delany and Bazley semi-infinite

$$Z_{DB} = 1 + 9.08\,(1000\,f/\sigma_e)^{-0.75} + i11.9\,(1000\,f/\sigma_c)^{-0.73} \qquad (1)$$

where f is frequency (Hz) and σ_e is effective flow resistivity in mks rayls/m.

(2) Delany and Bazley hard-backed-layer of thickness d m

$$Z(d) = Z_{DB} \coth(-ik_{DB}d) \qquad (2)$$

where

$$k_{DB} = \frac{2\pi f}{c}\left[1 + 10.8\,(1000f/\sigma)^{-0.7} + i10.3\,(1000f/\sigma)^{-0.59}\right] \qquad (3)$$

(3) Two parameter non-hard backed layer (ref. 4)

$$Z = (\pi\gamma\rho)^{-1/2}\,(\sigma_e/f)^{1/2}\,(1+i) + ic/(2\gamma\omega\Omega d) \qquad (4)$$

where γ is the ratio of specific heats in air,

ρ is equilibrium air-density

$\sigma_e = 4s_p^2\,\sigma/\Omega$

σ = flow resistivity

Ω = porosity

d = upper layer thickness

$\omega = 2\pi f$

s_P represents a pore shape factor ratio which must be frequency dependent as defined. However to be physically consistent in the low frequency limit, $4s_p^2 = 1$ (refs. 4 and 5). It should be noted that low frequency approximations have been used in the derivation of the above model.

For the purposes of the present computations, various values have been substituted for the constants resulting in

$$Z = 0.436\,(1+i)\,(\sigma_e/f)^{1/2} + 20\,\alpha/f \qquad (5)$$

where $\alpha = \dfrac{1}{\Omega d}$.

The level difference spectrum is computed from

$$LD = 20 \log |\, P_t/P_b \,| \qquad (6)$$

where

$$P_t \text{ or } P_b = \frac{e^{ikr_1}}{r_1} + Q\frac{e^{ikr_2}}{r_2} \tag{7}$$

$$Q = R_p + (1 - R_p)\, F(w) \tag{8}$$

$$R_p = \frac{\cos\theta - \beta}{\cos\theta + \beta}, \quad \beta = \frac{1}{Z} \tag{9}$$

$$F(w) = 1 + i\pi w e^{-w^2} \operatorname{erfc}(-iw) \tag{10}$$

$$w = (ikr_2/2)^{1/2} (\cos\theta + \beta) \tag{11}$$

r_1 and r_2 are direct and specularly reflected path lengths to the receiver of interest and θ is the angle of incidence for specular reflection.

Finally it should be noted that both level difference spectra used in this paper represent averages. The short range data represent averages in space and time. The data at 500 m represent averages in time. Three FFTs 0.75 s apart were taken from the time series and the data used represent the averages. The error bars in Figure 1 indicate the deviations between the three readings.

RESULTS

Figure 2 shows that although good fits to the data at short range may be obtained with σ_e = 1 000 000 mks rayls/m in equation (1) or σ_e = 300 000 mks rayls/m and α = 1000/m in equation (5), these values result in poor fits to the 500 m data. Figure 3 shows that σ_e = 900 000 mks rayls/m and d = 0.005 m in equation (2), and σ_e = 300 000 mks rayls/m, α = 300/m in equation (5) give tolerable agreement with both long and short range data. As was remarked in reference (3), we find that a five parameter non-hard backed layer model with the measured value of flow resistivity (1 100 000 mks rayls/m) gives reasonable agreement with the short range data but relatively poor agreement with the data at 500 m.

It should be noted that, as was remarked in ref. 3, the first dip in the measured level difference spectrum at short range is deeper than can be predicted with any impedance model tried so far.

DISCUSSION

In principle JAPE should have presented the opportunity for testing the use of short range level difference spectrum for ground characterization. Indeed combinations of parameters for two different two-parameter impedance models have been found that enable tolerable agreement with both short range and 500 m data. However closer inspection reveals several shortcomings in the data available at short range. Figure 4 shows that the chosen geometry results in predicted level difference spectra that are <u>insensitive</u> to wide variations of the parameters in the impedance model. Figure 5 shows that lowering the height of the upper receiver, to make it the same as that of the source, would have increased the sensitivity of the level difference spectrum predictions significantly. The calculations outlined in Appendix A show that after various simplifying assumptions it is possible to deduce an optimum geometry for short range ground characterization with a range of 1.75 m. The source and upper microphone heights should be between 0.19 m and 0.35 m.

Nevertheless it remains necessary to explain the fact that the first measured short range level difference spectrum dip is deeper than can be explained by impedance models alone. A possible explanation is the existence of a steep temperature gradient near to the ground during the measurement. Another possibility is directionality of the loudspeaker source.

CONCLUSIONS

Although short range level difference spectrum measurements have been used successfully for ground characterization over several soil types (ref. 2), there are problems with those obtained at the JAPE site. A major problem stems from the use of a short range measurement geometry which produces spectra that are relatively insensitive to the ground impedance in this case. In other locations, trial and error simulations of the sort shown in Figures 4 and 5 have been used to identify an appropriate geometry. Further work is reported here that enables a suitable choice of geometry without resort to such simulations or a need for prior knowledge of the likely range of flow resistivity of the ground of interest.

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APPENDIX A Determination of optimum geometry for short range ground characterization

According to the Weyl van der Pol formula the excess attenuation due to ground effect may be approximated by

$$EA = 20\log\left|1 + Q(r_1/r_2)exp(ik(r_1 - r_2))\right| \qquad (A.1)$$

For source and receiver at equal heights, h, and separation, d, and Q replaced by R_p (the plane wave reflection coefficient) the quantity in the modulus sign becomes

$$1 + |R_p|\sin(\theta)\exp[i(2kh(\sec(\theta) - \tan(\theta))] \qquad (A.2).$$

This is minimum when

$$2kh\sec(\theta)(1 - \sin(\theta)) + \phi = \pi \qquad (A.3)$$

Using the low frequency/ high flow resistivity approximation of the four parameter impedance model

$$Z = 0.436(1 + i)\sqrt{(\sigma/f)} \qquad (A.4)$$

it is possible to deduce that

$$|R_p| = \frac{\sqrt{\cos^2(\theta)+4B^4(f/\sigma)^2}}{\cos^2(\theta)+2B\sqrt{f/\sigma}\cos(\theta)+2B^2(f/\sigma)} \qquad (A.5)$$

and that

$$\phi = \tan^{-1}\left[2B\sqrt{(f/\sigma)}\cos(\theta)/\left(\cos^2(\theta) - 2B^2(f/\sigma)\right)\right] \qquad (A.6).$$

Substitution of (A.6) in (A.3) then leads to an equation for the frequency of the first ground effect dip in terms of the flow resistivity and the geometry. An example of the results of numerical solution of the resulting equation is shown in Figure 6.

Under the condition that (A.3) holds and defining

$$G = 1 - |R_p|\sin(\theta) \qquad (A.7)$$

it is necessary to find the value of θ for which $dG/d\sigma$ is maximum.
Figures 7 and 8 show examples of plots of $dG/d\sigma$ against θ for two values of σ.
If d = 1.75 m this shows that the upper receiver and source heights should be chosen to give 0.19m < h < 0.35m for greatest sensitivity to flow resistivity in the range 100 000 < σ < 1 000 000 Nsm^{-4}. Figure 9 confirms that the level difference spectrum is indeed very sensitive to variation in the ground parameters for h = 0.27 m and d = 1.75 m.

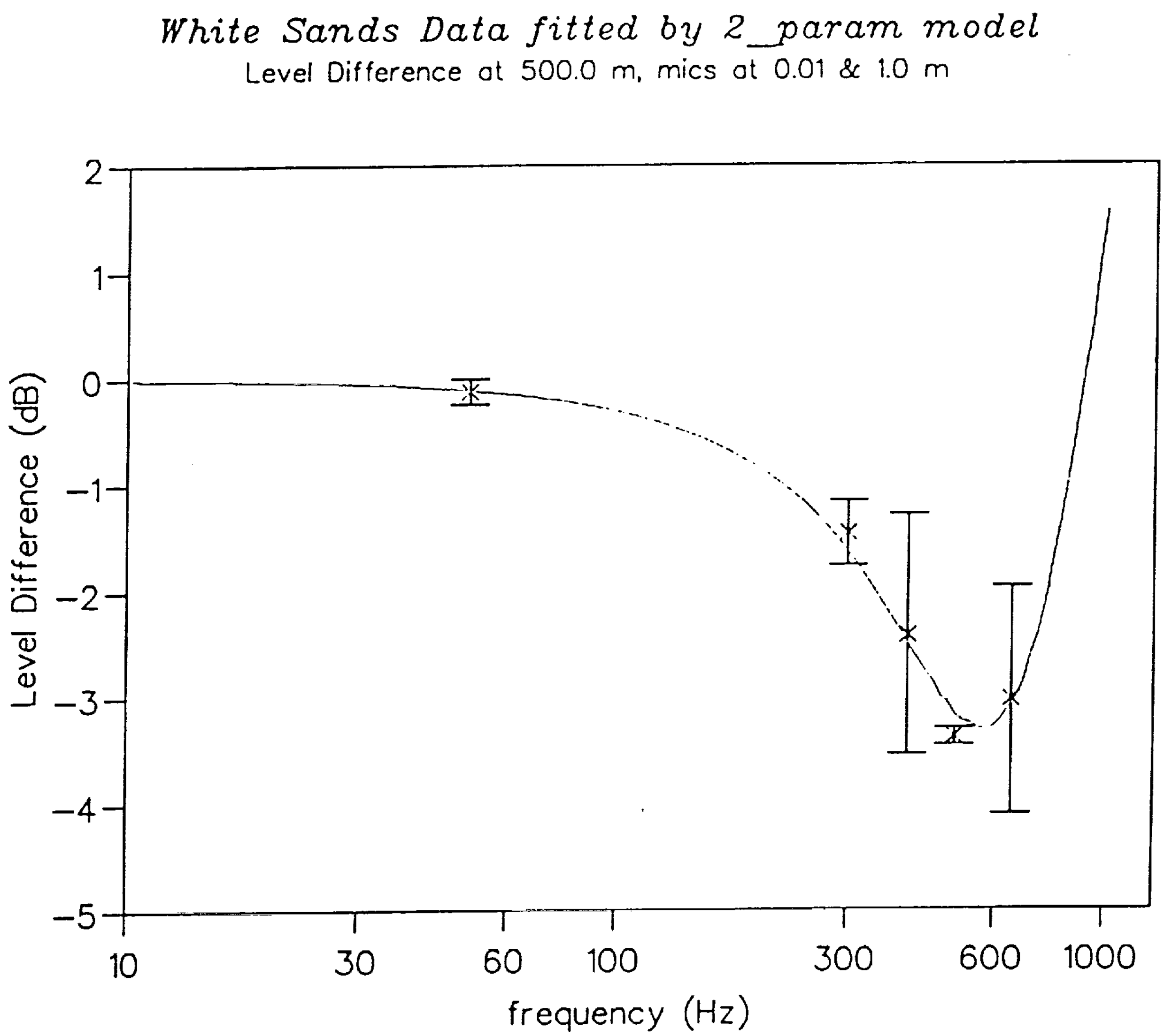
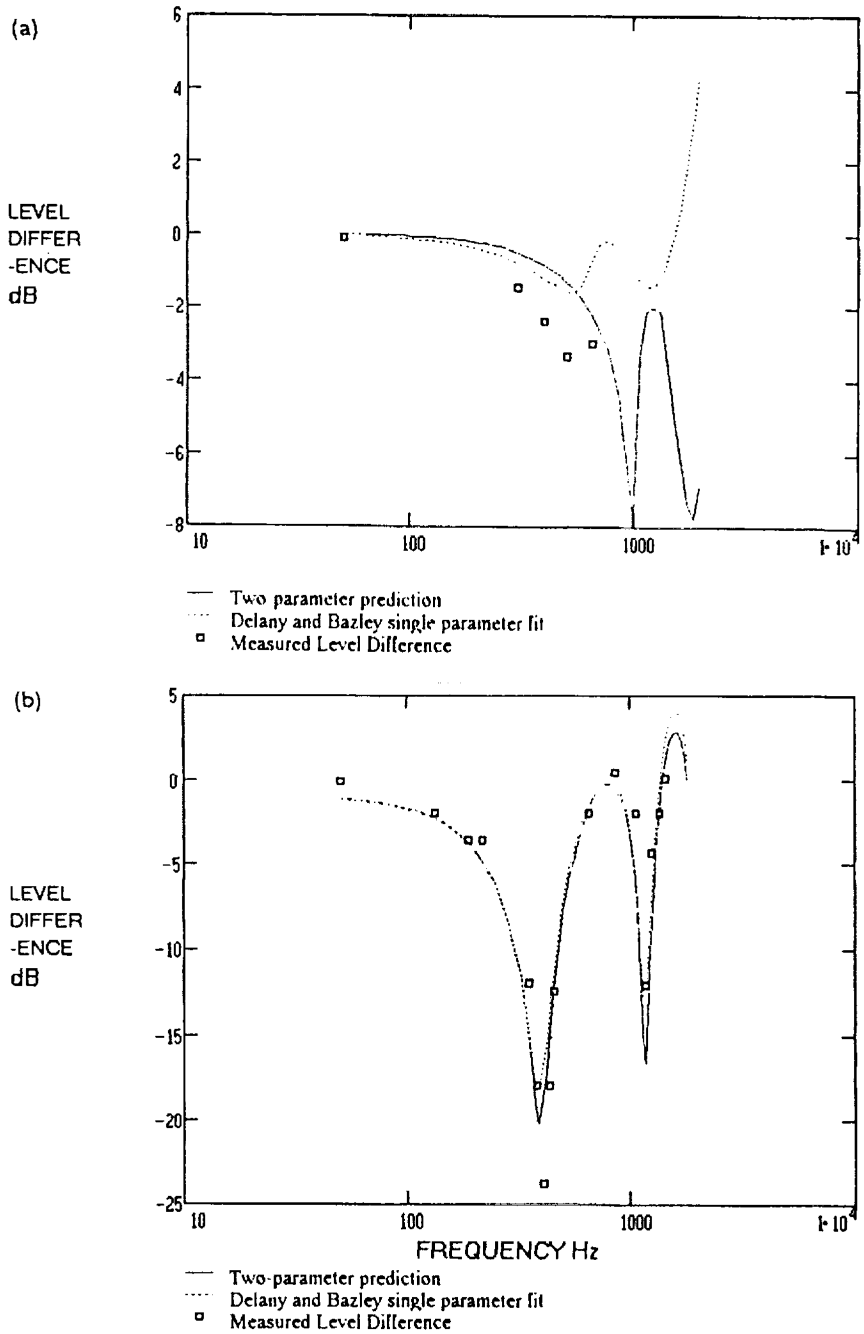
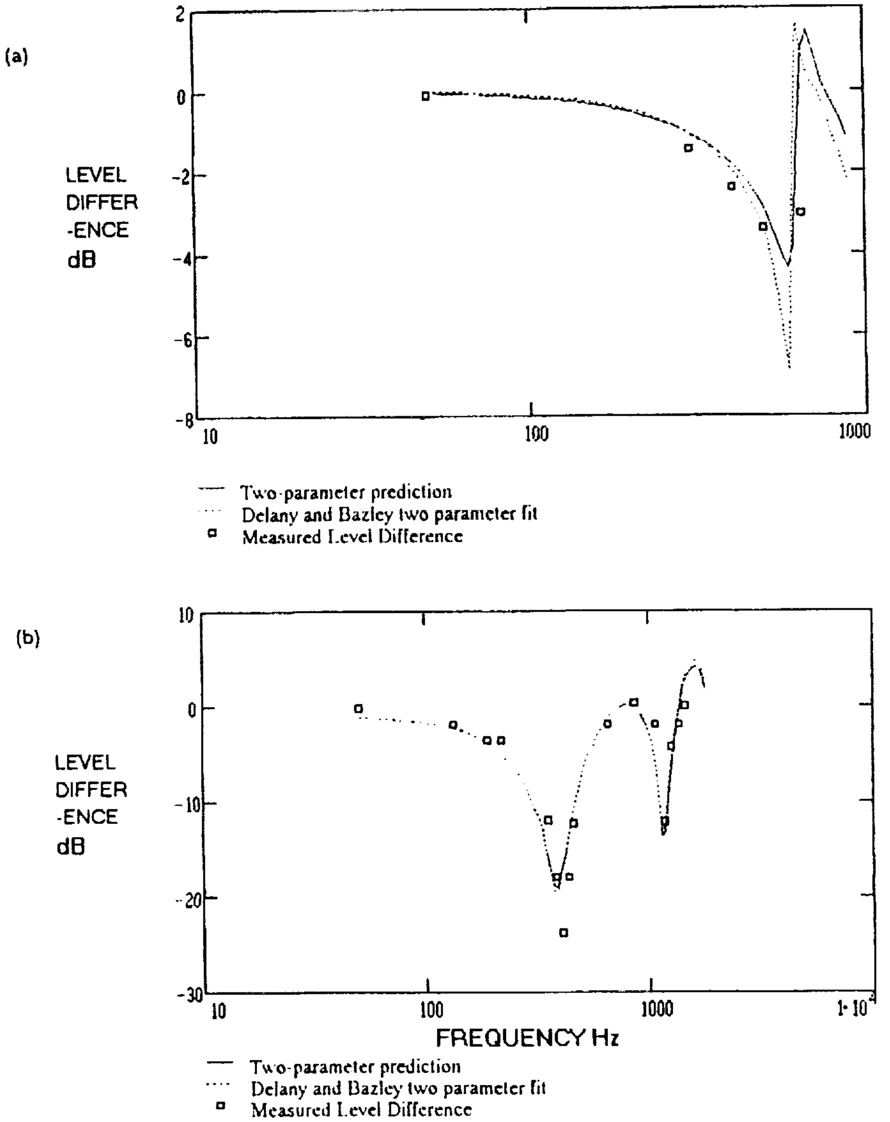


Figure 1. Pure tone data from the level difference at vertically-separated microphones at 1.0 and 0 m height with loudspeaker source at a height of 2 m and a range of 500 m. Error bars indicated range of data over several FFTs. A 2 parameter impedance model fit is shown using σ_e = 300 000 mks rayls m^{-1} and $\alpha_e = 10\ m^{-1}$.



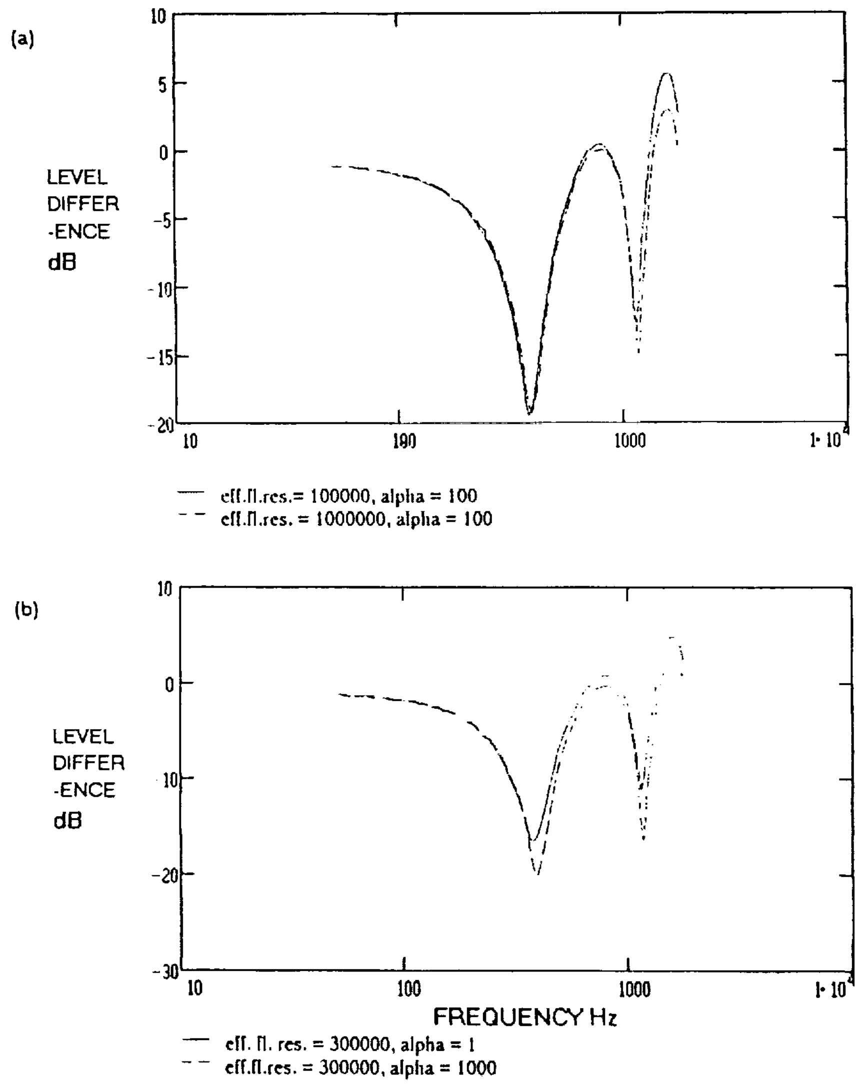
Level Difference geometries : (a) source height = 2.0 m, receiver heights = 1 m and 0.01 m, horizontal separation = 500 m.(b) source height = 0.45 m, receiver heights = 1 m and 0.1 m, horizontal separation = 1.75 m. Predictions using two-parameter fit with eff. fl.res. = 300 000 mks rayls/m and eff.alpha 1000 /m and Delany/Bazley with eff.fl.res. 1000000 mks rayls/m

Figure 2. Predicted and measured (u) level difference spectra (a) at long range; source height = 2 m, receiver heights 1 m and 0.01 m, horizontal separation 500 m and (b) at short range; source height = 0.45 m, receiver heights 1.0 and 0.1 m, horizontal separation 1.75 m. Predictions use two-parameter impedance model (σ_e = 300 000 mks rayls m^{-1}, α_e = 1000 m^{-1}, continuous lines) and single parameter Delany and Bazley fit (σ_e = 1 000 000 mks rayls m^{-1}, dotted lines).



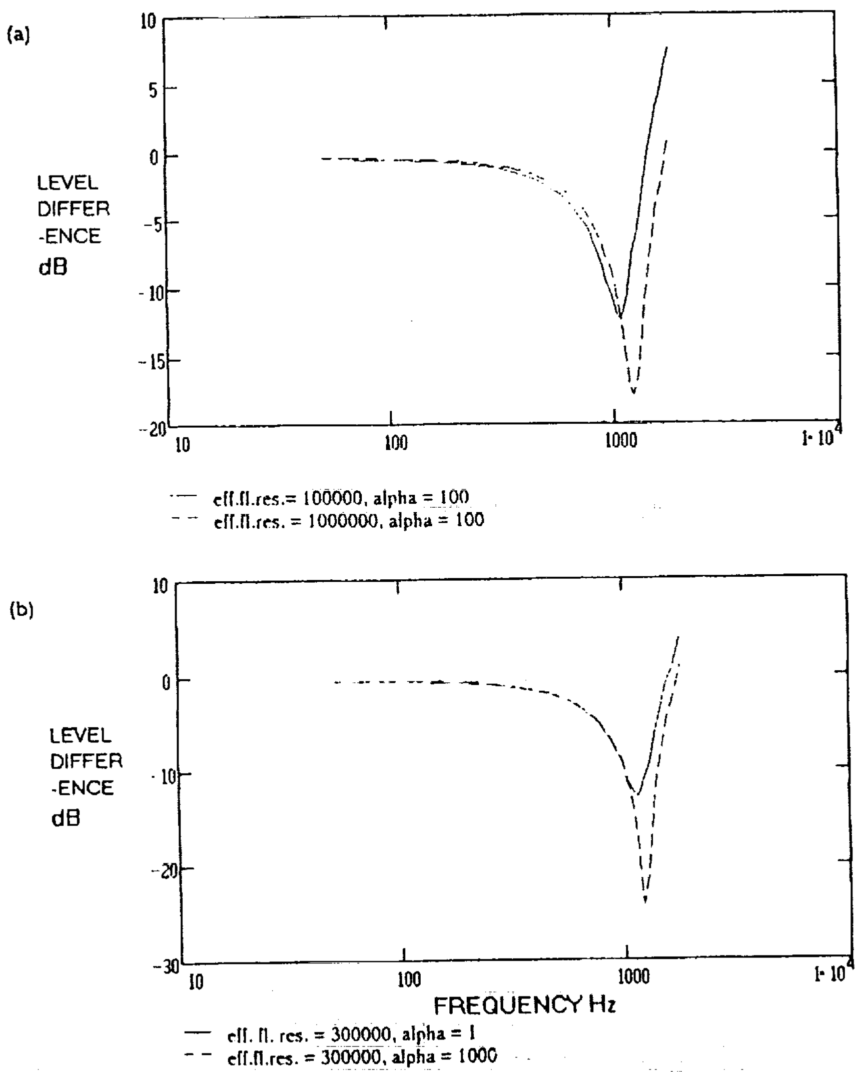
Level Difference geometries : (a) source height = 2.0 m, receiver heights = 1 m and 0.01 m, horizontal separation = 500 m.(b) source height = 0.45 m, receiver heights = 1 m and 0.1 m, horizontal separation = 1.75 m. Predictions using two-parameter fit with eff. fl.res. = 300 000 mks rayls/m and eff.alpha 300 /m and Delany/Bazley thin hard-backed layer fit with eff.fl.res. 900000 mks rayls/m and thickness 0.005 m

Figure 3. Predicted and measured level difference spectra at (a) long, and (b) short range. Continuous lines represent two-parameter fits with σ_e = 300 000 mks rayls m^{-1} and α_e = 300 m^{-1}. Dotted lines indicate 2-parameter Delany and Bazley fits with σ_e = 900 000 mks rayls m^{-1} and d = 0.005 m.



Level Difference geometry : source height = 0.45 m, receiver heights = 1 m and 0.1 m, horizontal separation = 1.75 m. Predictions using two-parameter impedance model, (a)Porosity variation parameter kept constant and effective flow resistivity increased by a factor of 10 (b) Effective flow resistivity kept constant, porosity variation parameter increased by a factor of 1000.

Figure 4. Predicted dependence of short range (original geometry) level difference spectra on impedance model parameters (a) α_e constant, σ_e varies by a factor of 10, (b) σ_e constant, α_e varies by a factor of 1000.



Level Difference geometry : source height = 0.45 m, receiver heights = 0.45 m and 0.1 m, horizontal separation = 1.75 m. Predictions using two-parameter impedance model.
(a)Porosity variation parameter kept constant and effective flow resistivity increased by a factor of 10
(b) Effective flow resistivity kept constant, porosity variation parameter increased by a factor of 1000.

Figure 5. Predicted dependence of short range level difference spectra for modified geometry (source height 0.45 m, receiver heights 0.45 m and 0.1 m, range 1.75 m) on impedance model parameters (a) α_e constant, σ_e varies by a factor of 10, (b) σ_e constant, α_e varies by a factor of 1000.

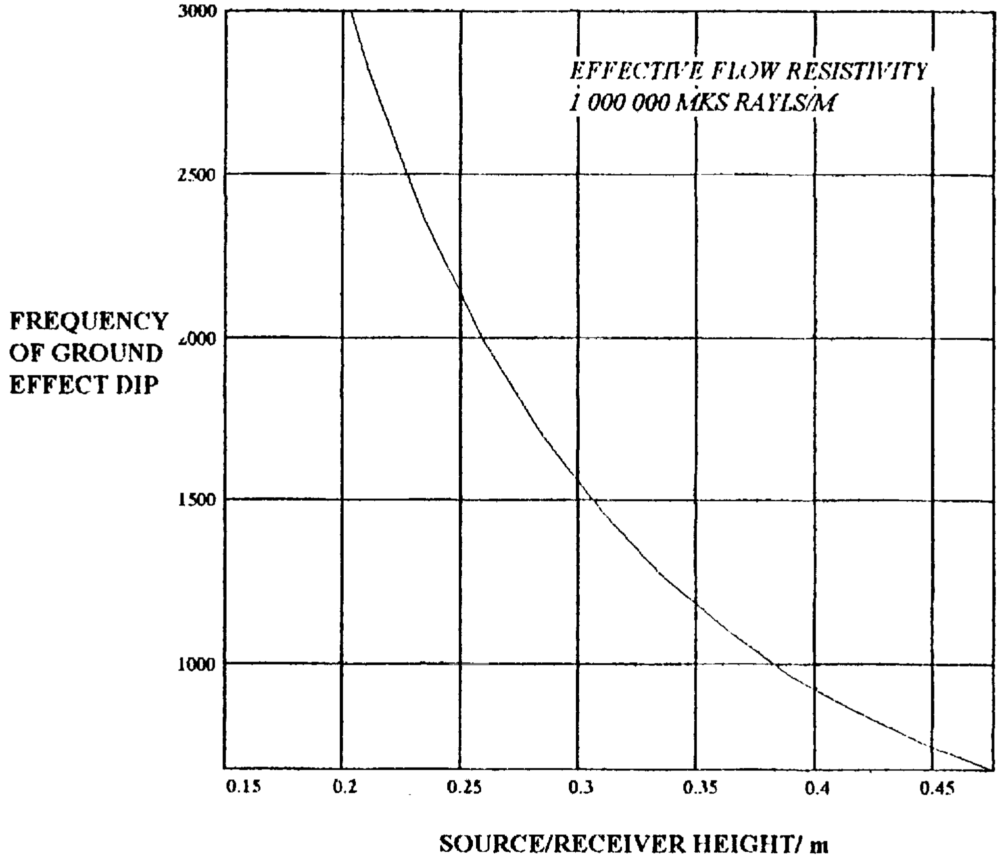
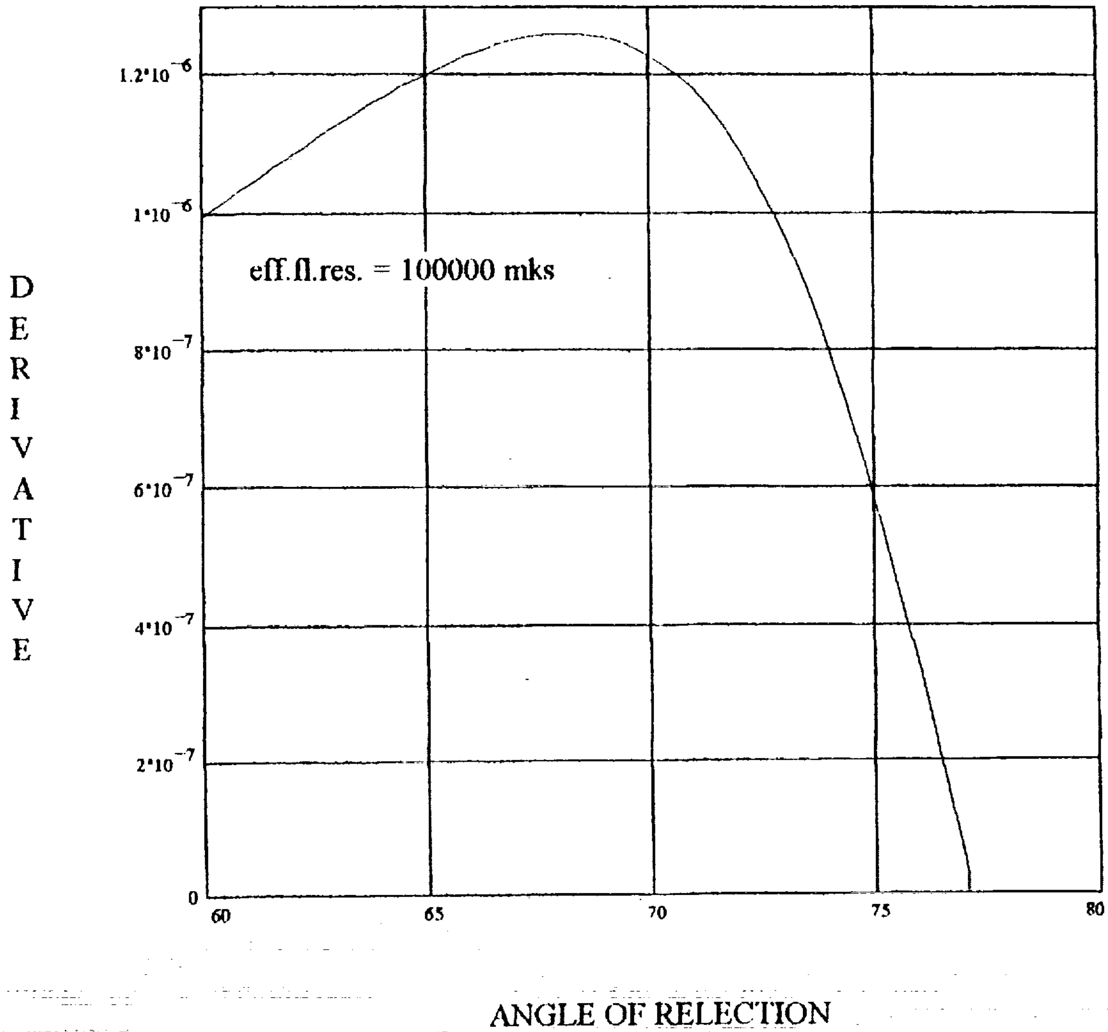
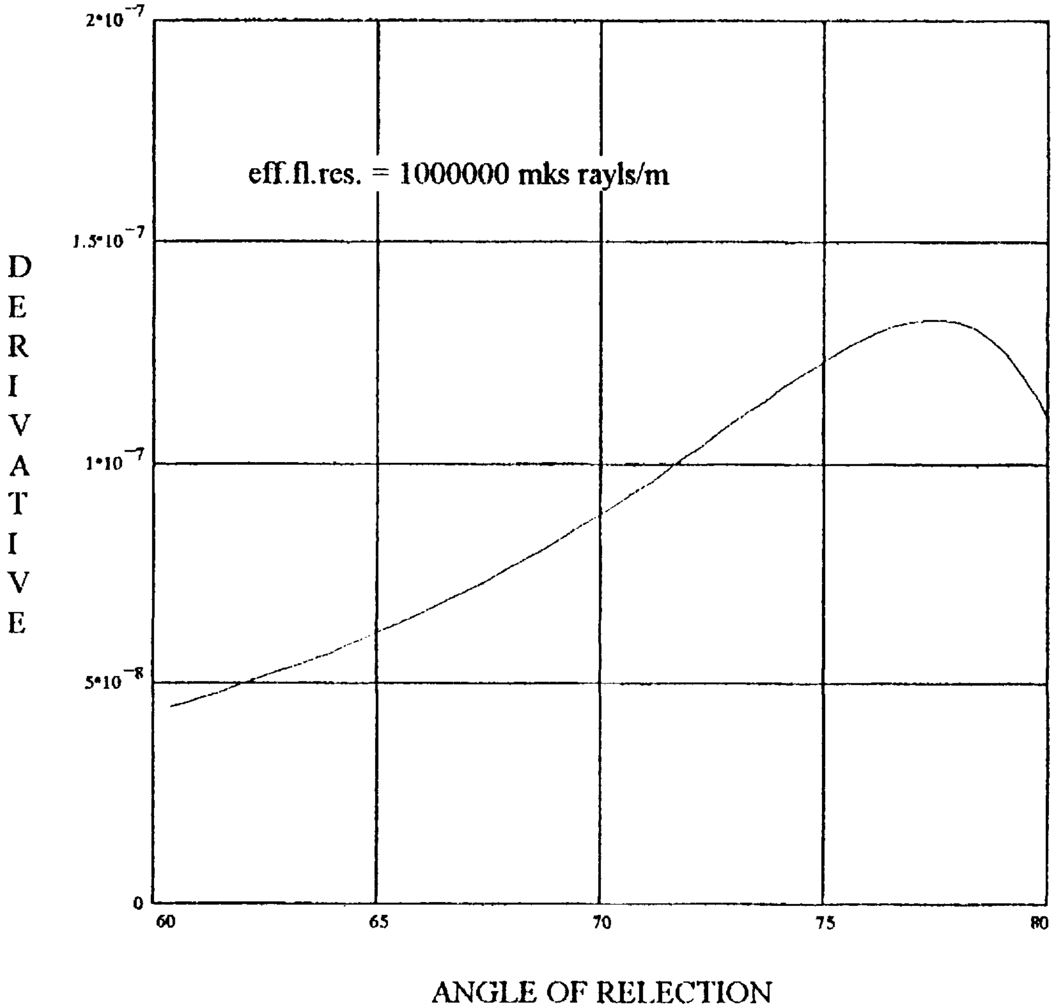


Figure 6. Predicted variation of frequency of (first) ground effect dip in excess attenuation with a height of direct (horizontal) path between point source and received over a surface characterized by a single parameter model with effective flow resistivity of 1000 000 NSm^{-4} and when source and receiver are separated by 1.75 m.



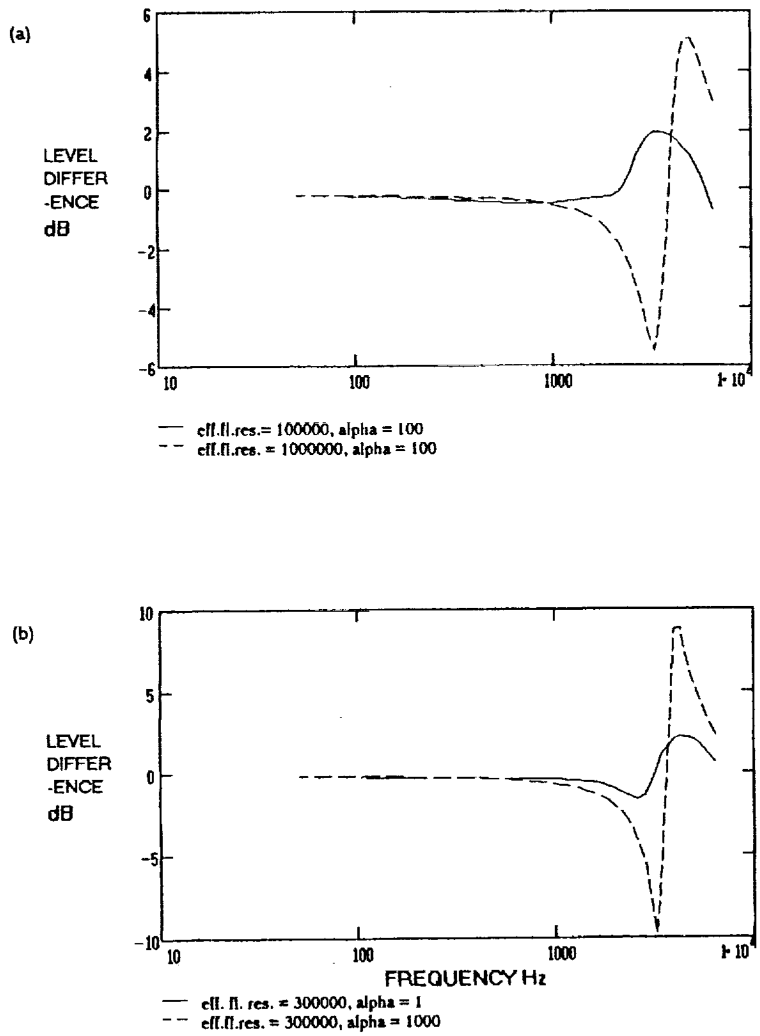
Plot of derivative of excess attenuation with respect to flow resistivity against specular angle for equal source and receiver heights.

Figure 7. Variation of derivative of excess attenuation (at frequency of first ground dip) with respect to flow resistivity as specular reflection angle varies for equal source and receiver heights over a ground with effective flow resistivity 100 000 NSm^{-4}. Maximum at 68 ° implies H = 0.35 m for separation of 1.75 m.



Plot of derivative of excess attenuation with respect to flow resistivity against specular angle for equal source and receiver heights.

Figure 8. As for Figure 7 but effective flow resistivity is 1000 000 NSm^{-4}. Maximum at 78 ° implies H = 0.19 m for separation of 1.75 m.



Level Difference geometry : source height = 0.27 m, receiver heights = 0.27 m and 0.1 m, horizontal separation = 1.75 m. Predictions using two-parameter impedance model.
(a)Porosity variation parameter kept constant and effective flow resistivity increased by a factor of 10
(b) Effective flow resis tivity kept constant. porosity variation parameter increased by a factor of 1000.

Figure 9. Sensitivity of level difference spectrum to ground parameters for source and upper receiver height = 0.27 m, separation = 1.75 m, lower receiver height = 0.1 m.