THE EFFECT OF RESISTIVITY ANISOTROPY ON EARTH IMPULSE RESPONSES

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INTRODUCTION

Resistivity anisotropy arises through a variety of scales from micro (e.g. grain size, pore water connectivity) to macro (e.g. laminated sand-shale sequences). For general anisotropy the physical property under consideration may vary in all three spatial directions. The simplest problems involve transverse anisotropy where resistivity at a point in any direction in a plane differs from the value perpendicular to the plane. We are here concerned solely with transverse anisotropy with a vertical axis of symmetry (TIV) so that resistivity at a point has a constant magnitude in any horizontal direction. Induction logs, laterolog and LWD (logging-while-drilling), at least in vertical wells, may be used to examine TIV in particular and these well log results often differ from indirect determinations of resistivity through DC resistivity and general EM surveying. Much of the earlier EM literature considered resistivity as isotropic but there is now great emphasis on the inclusion of anisotropy in modeling and inversion studies. In this paper we consider the effects of transverse anisotropy (specifically TIV) on the earth's electromagnetic impulse and step responses.

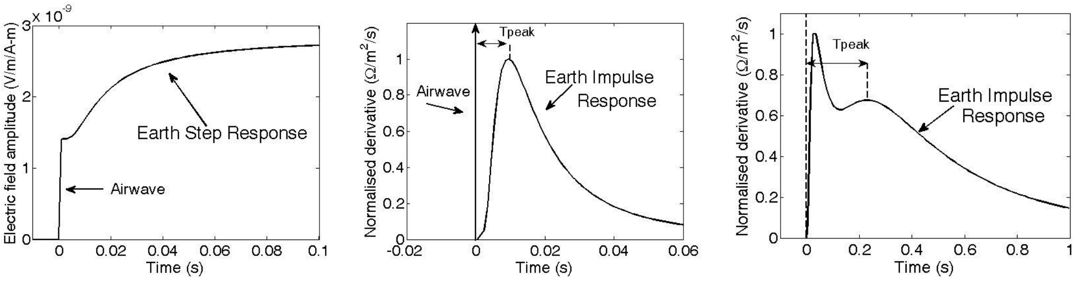
THE MULTI-TRANSIENT ELECTROMAGNETIC METHOD

In the multi-transient electromagnetic method (Ziolkowski et.al, 2007) current is injected into the ground between two electrodes (the source) and the resulting potential difference is measured between two further electrodes (the receiver). The four electrodes are collinear and the distance between the mid-point of the source electrodes and the mid-point of the receiver electrodes is termed the offset. Transient current injection at the source may take the form of a step change in current, such as a reversal in polarity of a DC current, or a coded, finite-length sequence such as a pseudo-random binary sequence (PRBS). For any form of transient current injection, measurements are made of both the source current and the receiver voltage and deconvolution determines the earth's impulse response. Integration of the impulse response yields the earth's step response.

Earth Step and Impulse Responses

The form of earth response functions may be illustrated by calculating the impulse and step responses at some offset for the simplest case of a uniform, isotropic halfspace. Example impulse responses for land and marine are shown in Figure 1.

On land the impulse response comprises a so-called airwave (which travels along the ground/air interface at a scale comparable to the velocity of light and so arrives at time t=0) followed by a response resulting from diffusion through the resistive subsurface. These two components are immediately separable. In the marine case the earth response comprises travel through the sea water, through the sea/air interface and through the subsurface. All three parts persist throughout the entire record. The peak value and arrival time of the peak value (Tpeak) depend on the subsurface resistivity.



(a) (b) (c)

Figure 1. (a) Land step and (b) land impulse responses calculated at an offset of 1500 m for a uniform halfspace of resistivity 30 Ω m. The earth impulse response has been normalized by its peak value of 5.49 10^{-8} $\Omega m^{-2} s^{-1}$. (c) Marine impulse response calculated at an offset of 1500 m for a uniform halfspace of 1 Ωm overlain by 100 m of sea water of resistivity 0.3125 Ωm. The earth impulse response has been normalized by its peak value of 1.40 10^{-10} $\Omega m^{-2} s^{-1}$. Note the different timescales.

THE EFFECTS OF ANISOTROPY

For the transverse anisotropy under consideration (TIV) the vertical resistivity ρ_v and the horizontal resistivity ρ_h define the anisotropy factor

$$\lambda = \sqrt{\frac{\rho_v}{\rho_h}}$$

with typical values between 1 and 5. The square of the geometric mean resistivity is $\rho^2 = \rho_v \rho_h$. We may now consider three special ways of varying anisotropy – keeping ρ_v, ρ_h or ρ^2 constant. We describe these cases as:

ρ_h^c: ρ_h=constant, ρ_v and ρ^2 increase with increasing λ

ρ_v^c: ρ_v=constant, ρ_h and ρ^2 decrease with increasing λ

ρ_c^2: ρ^2= constant, ρ_h decreases and ρ_v increases with increasing λ

Effects on a uniform halfspace step response for these three cases of varying anisotropy are shown in Figure 2. The effects are dramatic. The airwave (initial step $E(0)$) depends only on the horizontal resistivity ρ_h (since the airwave is the Transverse Electric (TE) mode) whereas the late time DC value ($E(\infty)$) depends only on the geometric mean. Using results from Wilson (1997) for an isotropic halfspace of resistivity ρ

$$E(0) = \frac{\rho}{2\pi r^3} \text{ and hence} = \frac{\rho_h}{2\pi r^3}, \qquad E(\infty) = \frac{\rho}{\pi r^3} \text{ and hence } = \frac{\sqrt{\rho^2}}{\pi r^3}.$$

This provides a method of determining the anisotropy of the halfspace as

$$\lambda = \frac{\sqrt{\rho^2}}{\rho_h} = \frac{1}{2}\frac{E(\infty)}{E(0)}$$

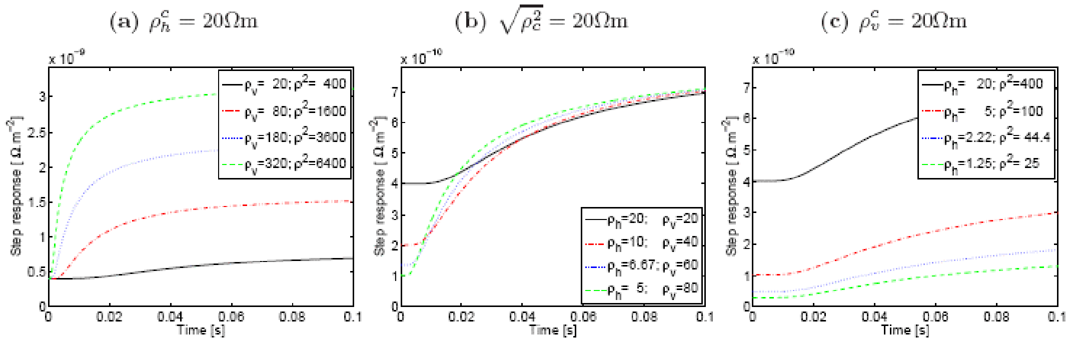


Figure 2. Effects of anisotropy on step responses at an offset of 2 km for a uniform halfspace. λ =1 (solid black), λ =2 (dash-dotted red), λ =3 (dotted blue) and λ =4 (dashed green). The isotropic case (solid black) is the same in all three cases.

Effects on the impulse response for the same models as above are shown in Figure 3. These graphs are the derivatives of those in Figure 2 but the airwave delta function (derivative of the initial step) is not shown.

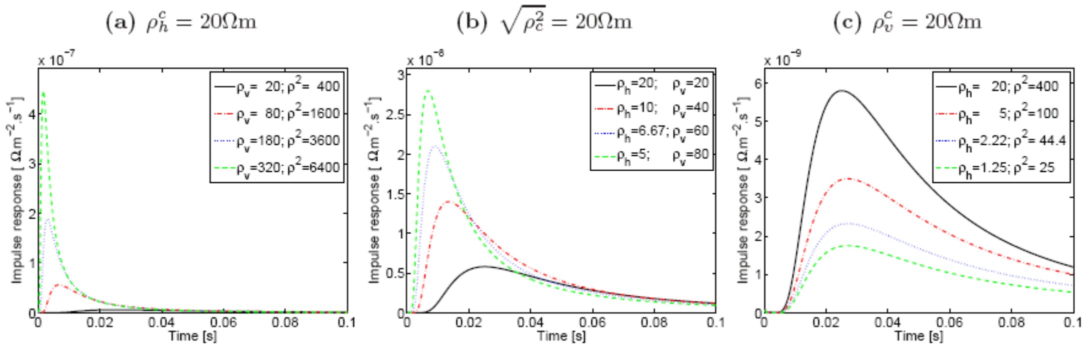


Figure 3. Effects of anisotropy on impulse responses at an offset of 2 km for a uniform halfspace (land case). λ =1 (solid black), 2 (dash-dotted red), 3 (dotted blue) and 4 (dashed green). The isotropic case (solid black) is the same in all three cases.

Marine impulse responses are also much affected by anisotropy as shown in Figure 4. The airwave part is seen to depend mainly on ρ_h and the earth response (overlapping with the airwave) is more dependent on ρ_v.

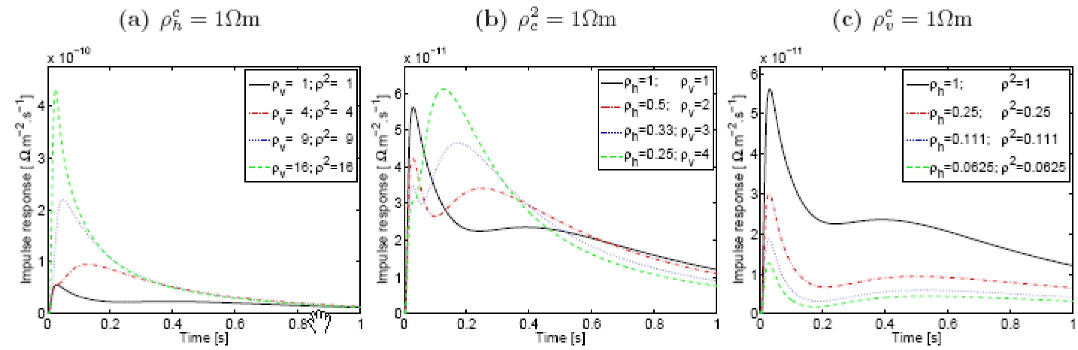


Figure 4. Effects of anisotropy on impulse responses at an offset of 2 km for a uniform halfspace (marine case, water depth = 100 m). λ =1 (solid black), 2 (dash-dotted red), 3 (dotted blue) and 4 (dashed green). The isotropic case (solid black) is the same in all three cases.

IMPLICATIONS FOR THE INVERSION OF MTEM DATA

We now seek to determine the implications of inverting MTEM data acquired over an anisotropic subsurface with an isotropic inversion routine. Anisotropic data were generated from a model comprising a background geometric mean resistivity of 20 Ωm with an embedded target layer 25 m thick with geometric mean resistivity 500 Ωm whose top was at a depth of 500 m. An anisotropy value λ =2 was used for all layers. Step responses were generated for the three offsets 1.5 km, 2 km and 2.5 km. Isotropic inversions were made for these three offsets individually (single-trace inversion) and for all three simultaneously (multi-trace inversion) see Figure 5.

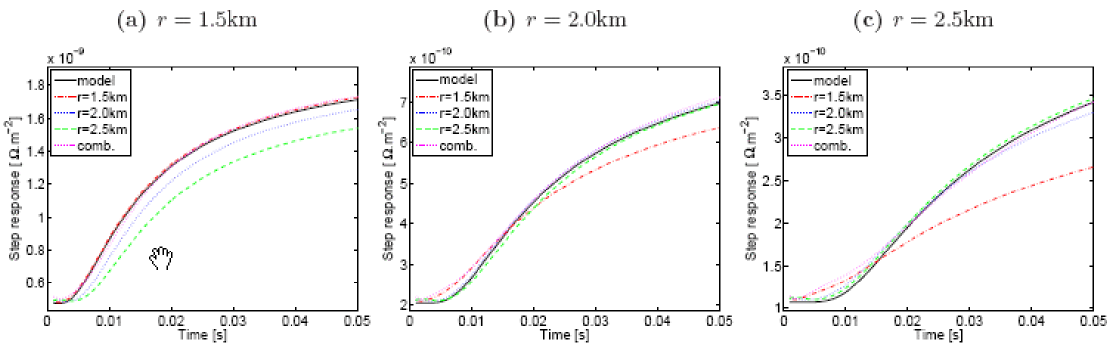


Figure 5. Synthetic step responses from the model described in the text (solid black) and isotropic inversions for three offsets singly and in combination. Also shown are responses at each offset from all the inversion models.

Figure 5 shows that for any single offset an isotropic model can be found that fits the anisotropic response data. The target in these isotropic inversion models is always shallower than in the original anisotropic model – the smaller the offset, the shallower the target. (A survey over a calibration well could be used to determine anisotropy values that yield the correct target depths.) The model derived from inverting the response at one offset was used to calculate the response at other offsets and there are clear misfits (Figure 5). Similarly the use of all three offsets in a multi-trace isotropic inversion failed to produce a model satisfying all the anisotropic data.

CONCLUSIONS

Inversion at a single offset cannot distinguish between isotropy and anisotropy and can give misleading results concerning target depths. Thus proper interpretation will require anisotropy to be included as part of any inversion scheme. Since single offset data cannot determine anisotropy, simultaneous inversion of multi-offset data will be a necessity. Layer anisotropies will therefore be included as free parameters in forthcoming inversions. Where possible, a survey over a calibration well may be used to determine anisotropy values that yield the correct target depths.

REFERENCES

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