Estimating the energy range along a surficial waveguide

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Summary

It is know that surface layers may act as waveguides to the propagation of EM energy. Here we analyze the case where a concrete pavement acts as a weak guide of EM waves over a higher permittivity soil, i.e., not a true waveguide as the steady state is never reached. We can estimate a phase velocity dispersion curve from the F-K panel of a common-shot profile in order to invert for both the waveguide refractive index and thickness. In this paper though we concentrate in analyzing how far the guided energy reaches, before it dies out for longer offsets. For that we compare two polarizations of the EM field and produce credible estimate for the maximum useful offset.

Introduction

Dispersive wave propagation may occur in the uppermost layer if its thickness is comparable to or smaller than the wavelength, and its lower boundary is a strong reflector. In this case EM waves will be trapped in the waveguide, traveling in a modal fashion (Annan et al., 1975). As in all cases the waveguide is overlain by air either the substratum has a lower or a significantly higher permittivity than the waveguide's (Arcone et al., 2003; van der Kruk et al., 2006). A low-velocity layer of wet soil over a higher velocity layer of sand and gravel is a studied example of the first case (Arcone et al., 2003; van der Kruk et al., 2006). An ice layer over water is an example of the second case (e.g., van der Kruk et al., 2007).

In a companion paper (Peche et al., 2009) we have inverted the phase velocity dispersion curve from the F-K panel of a TE common-shot profile for both the waveguide refractive index and thickness. In that paper we had estimated the energy range with offset through cross-correlation of traces. Note that although the underlying layer has a higher permittivity, enough to provide strong enough reflection, the energy leaks downwards and is quickly absorbed by a high-loss substratum. Here we confront the cross-correlation findings with another approach made possible by analyzing the TM data.

This paper deals with a leaky waveguide where total internal reflection occurs only at the upper interface beyond the critical angle. Our experimental data were obtained over a concrete pavement overlying an oxisoil.

Numerical Results

Consider the case of the transmission of EM waves weakly bound in a guiding planar slab situated on the top of a semi-infinite half-space, interfacing with air at its top boundary. The x-axis is perpendicular to the interfaces with origin at half-width of the 2r thick slab, otherwise infinite. The z-axis points towards the direction of moveout, or observation point. The EM waves are launched into the slab by a dipolar transmitting antenna coupled to the slab's free interface at z = 0. The transmitting antenna axis can be oriented either along the y-axis or along the z-axis, generating the TE or the TM modes, respectively. The basic geometry is depicted in Figure 1.

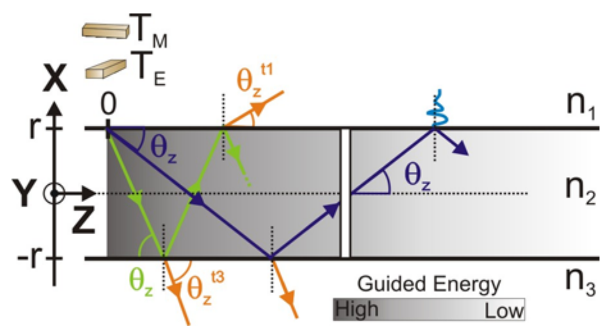

Figure 1. Schematic of trajectory and angle by the antennas coupling.

A guiding planar slab on the top of a semi-infinite half-space, with air at its top boundary. The transmitting antenna launch the TE or TM modes into the slab through coupling with its free interface at z = 0, depending on axis orientation either along the y-axis or along the z-axis, respectively. We assume a hierarchal refractive system $n_1 = 1 < n_2 < n_3$ where total reflection can only occur at the top boundary (blue ray). There are three possibilities of ray trajectory in the continuum of angular distribution defined by the antenna coupling at z = 0, all loosing energy through refraction into the half-space and/or air. Green ray represents the case where energy is refracted into the air. Blue ray represents totally reflected energy reaching the top boundary at angles bigger than critical angle. An evanescent field propagates away from the point of total reflection into the air. The third case is when ray hits the top boundary at the critical angle, being refracted in air at grazing angle and eventually being refracted back into the slab. Note in the slab (Figure 1) that the blue ray pass though a gap, it will be important to explain the results.

The EM waves diffract into the slab through the antenna coupling with an angular distribution that depends on the refractive indexes n_1 and n_2 (Annan et al., 1975; Arcone, 1995), where

$$n_i = \sqrt{\varepsilon_i / \varepsilon_0} \qquad (1)$$

where n_i, ε_i , i = 1, 2, 3, and as the slab interfaces with air on its top surface then, $n_1 \equiv n_0$. For the slab to be considered as a true waveguide we need to have a hierarchy of refractive indexes as $n_1 < n_2 > n_3$. In this case all rays traveling with angles beyond the critical angle will have their zigzag trajectories entirely confined in the slab, being partially refracted, loosing energy to the surrounding media as they travel along the slab.

Assume a hierarchal refractive system $n_1 = 1 < n_2 < n_3$, where total reflection can only occur at the top boundary (Figure 1). We consider further that the slab is thin with respect to its internal average wavelength, which together with the energy loss across boundaries indicate a leaky modal propagation with moveout. Such slab will only be able to propagate the fundamental modes of the two polarizations states, the TE or the TM modes, depending on antenna orientation either along the y-axis or along the z-axis, respectively. Even with no absorption in the slab the energy is lost fairly quick with moveout, remaining entirely confined to a transient process. The refracted power turns the slab into a radiator limiting its ability to conduct power efficiently and prevents it to reach the steady state of a true waveguide.

Let´s restrict the numerical problem to the TE-mode, i.e., antenna orientation along the y-axis. Assume a surficial concrete slab of $n_2 = 2.8$ on the top of a more conductive half-space $n_3 = 4.5$. Figure 2 shows the results of our model for two thicknesses r = 0.5, 0.1 m and a central frequency of 100 MHz. As the surficial layer half-width r changes from 0.5 m to 0.1 m the reflection of the bottom of the layer virtually disappears as all the energy becomes channeled in the thinner surficial layer. The dispersion of the guided waves phase velocity can be seen in the right panel of Figure 2. A phase velocity dispersion curve can obtained picking the maxima from the phase velocity spectrum (Park et al., 1998) or from a F-K panel (Strobbia & Cassiani, 2007).

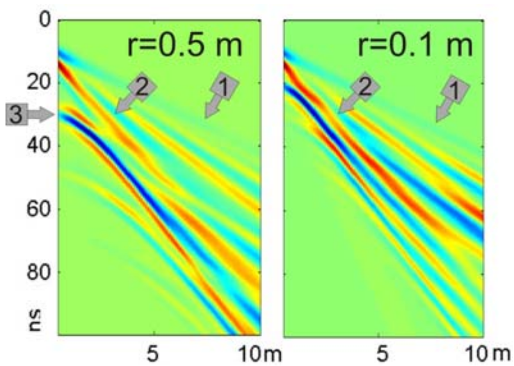

Figure 2. CMP sections of the modeled concrete slab ($n_2 = 2.8$) on the top of a half-space ($n_3 = 4.5$). The air (1) and slab (2) direct.

Experimental Results

GPR data were collected on a concrete floor of an abandoned factory in the City of Manaus, Brazil. It remained in place just the factory floor and several 0.36 m high prismatic concrete supports that once served as base for the roof pillars. The concrete floor has two half-thicknesses r = 0.05, 0.08 m, overlaying an oxisoil engineered into a sizeable flat plateau where once stud the factory. The free surfaces of the two concrete floors are not flush.

Data were collected using a Sensors & Software GPR with 100 MHz antennae, 800 ps sampling rate, 32 stack and a spatial interval of 0.1 m.

The concrete floor is made up of rectangular sections of 6.05 x 2.26 m^2. We have collected TE and TM data along a single profile that cuts the rectangular sections along their smallest dimension, having its midpoint at the junction of the two thicknesses. We are going to concentrate on the dataset obtained on the thinner concrete.

Figure 3 shows the TE and TM results on the thinner concrete. Note the absence of reflections for both polarizations and a reflection off one pillar appearing as an artifact with an apparent velocity greater than *c*. Note also a bright spot at the end of the linear moveout on the TM section.

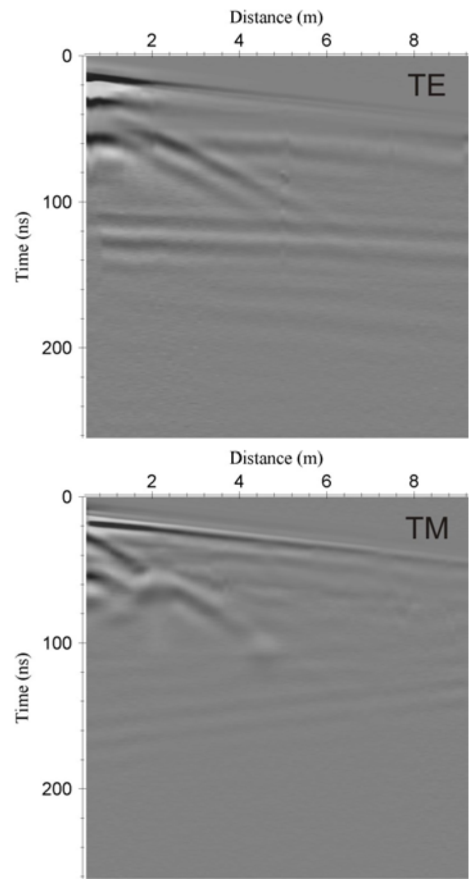

Figure 3. TE, upper panel, and TM, lower panel, results on the thinner concrete.

Estimation of energy range

We can estimate the energy range independently for the two polarizations. From Figure 3 it is clear that the maximum moveout depends on polarization; the energy reaching further away for the TE mode.

We proceed by F-K filtering the TE and TM modes to restrict the data to the channeled energy. We can cross-correlate the TE mode traces against offset to estimate the maximum offset the energy travels before falling below the detection limit of our instrument. Figure 4 shows the TE filtered data and the cross-correlation of each trace against all other traces. From Figure 4 it is clear that channeled energy reaches offsets of about 6 m.

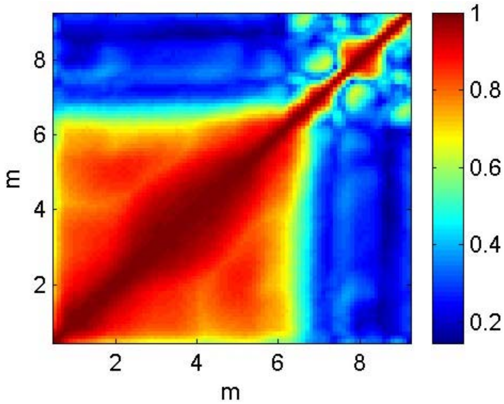

Figure 4. Cross-correlation of each trace against each other. Note that the correlation values repeat across the diagonal.

Of course we can repeat the same procedure for the TM polarization. Here we take a different route instead. We estimated the maximum of the envelope for the frequency range 20-110 MHz and plot it against offset, Figure 5. Following this procedure we get two minima for the maximum of the envelope at 1.8 and 4.2 m. As we have measured distance in the field using the distance between the electronic box of the antennae, we should add 0.3 m to the distances in Figure 5 to obtain exactly the length of the concrete slabs along the profile: 2.26 m. This indicates that energy travelled through, at least two concrete patches, i.e., about 4.5 m.

Figure 5 dose explain the seemingly odd behavior of the TM data, see Figure 3, with offset. The linear moveout of the TM mode reaches a minimum at offsets corresponding to the gaps between two concrete slabs. Evidently this is only seen at the TM mode as the electric field is discontinuous across the gaps, unlike the TE case where it is continuous.

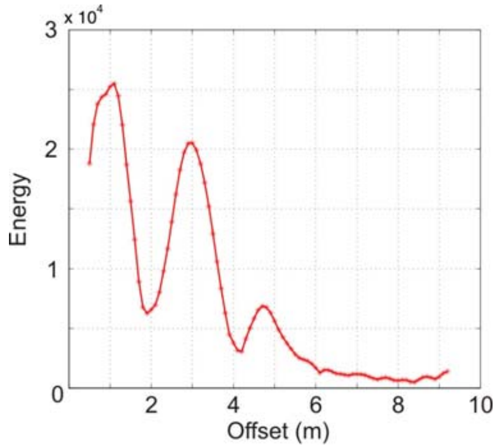

Figure 5. Maximum of the envelope for the frequency range 20-110 MHz against offset. The two minima at 1.9 and 4.2 m correspond to the gaps between two concrete pads.

Conclusions

Two surveys were made with different types of polarization (TE mode and TM mode), the TE mode is easy to observe in linear moveout that the dispersion still in the slab, unlike the TM mode, where they appear discontinuous regions.

The modeling done for the TE mode, confirms the wave scattering for the slab with a thin.

For the TM mode was made a cross-correlation and found that the electromagnetic wave propagates inside the slab, thus suggesting a behavior of waveguide.

In corroboration with this idea above of the TM mode, an analysis was made of the envelope showing two regions of minimum exactly in the region where the gaps in the slab are.

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