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Nondestructive Testing Resolution: Electromagnetic Waves versus Seismic Ones

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ABSTRACT

The practical limits on resolution of images from seismic or radar (electromagnetic) data depend on the spectrum of the source pulse, the incompleteness of the recording geometry, and the fidelity with which one can model the reference medium. These factors together prevent one from recovering a point image from data produced by a point diffractor in a given body. A simple imaging formula quantifies the effect of the source pulse spectrum, showing that spatial wavelet extent in an imaged volume is related to the product of the local velocity and the period of the propagating pulse. A general scheme for estimating the effect on resolution of the recording geometry is applied to various recording geometries in modeled concrete slabs for seismic and electromagnetic waves.

The penetration of electromagnetic waves, generated from Radar instruments, into media like concrete, have similar kinematic properties to the seismic (ultrasonic) ones, differ in their dynamic and response behavior. Using finite difference numerical modeling, as well as physical observations, we realized that features in media, such as voids, appear differently on GPR sections versus seismic ones. Part of the difference is attributed to the wave velocity difference for the two waveforms for air and water filled voids, resulting in difference in appearance and resolution.

Despite the much higher frequencies associated with Radar electromagnetic waves, the higher frequencies are well compensated by the high velocity of such waves resulting in wavelengths similar to those experienced in seismic experiments. Nevertheless, due to the single mode nature of electromagnetic waves, we obtain better scattering behavior (cleaner) using radar data than what can be obtained using seismic ones. The scattering response of seismic waves includes the conversion of part of the energy to other modes (i.e. shear modes). These modes can potentially provide additional information, but requires careful analysis.

INTRODUCTION

A form of non-distructive testing (NDT) has been applied in the geophysical community since the early 1900's. Specifically, we measure the physical properties of the Earth subsurface or the Earth's response to a physical excitation without destroying the Earth with drilling or any excavation. Clearly, the Earth's subsurface is far more complicated than media that are typically investigated via NDT in the conventional sense. The medium inhomogeneity, the problem dimensionality, and the acquisition limitations are among the realities that complicate the Earth's subsurface investigation. However, the resolution expected from typical geophysical surveys is far less than what is usually required in conventional NDT investigations. Thus, resolution is particularly important in NDT investigation especially in mapping voids and cracks location and size

Non destructive testing (NDT) methods for investigating the integrity and content of structures have gained momentum the past few years (Laurens et. al., 2003; Annan, 2003). The purpose of these methods is to obtain information on a given structure with out causing any destruction or damage to the investigated area, similar to geophysical applications. This, again, is accomplished by measuring the physical properties or the response of such material to physical excitation, which will provide us information on content and behavior. Among the usually investigated physical properties are the response of structure to electromagnetic waves (i.e., the radar method) and the response to seismic waves (i.e., the IE method). Electromagnetic waves are of higher frequency and speed (light-like speeds) compared to seismic ones, but has limited penetration capability. The high speed allows for fast gathering of data through profile type acquisition. On the other hand, seismic waves are of lower frequencies and speed but have better penetration capability. Both of these methods are discussed here.

Resolution has two common definitions. The first of these relates to determination of the position of a reflector in time or space. Resolution by this definition is inversely proportional to pulse width or sharpness of the wavelet and, potentially, directly related to the bandwidth of the frequency spectrum. The second definition of resolution relates to determination of the spacing of close features such as thin anomalies (cracks or voids). This type of resolution is determined by the Rayleigh criterion which inversely relates resolution to wavelength.

In this paper, I discuss the theoretical background for acquiring seismic (acoustic) data and electromagnetic (radar) data. Considering the two methods have similar acquisition setting, I discuss the limits of resolution for both methods using acoustic numerical modeling examples. These results are equally applicable to seismic or radar data. However, velocities, attenuation, and pulse frequencies of the two methods vary considerably and thus resolution of determining voids within a concrete slab is different. I show the difference using synthetic and physical data.

THEORY AND CAPABILTIES

We investigate here the resolution for two popular NDT methods: The seismic (acoustic) based methods like impact echo (IE) and the electromagnatic-based methods like radar. Typically seismic methods are used to investigate cracks, voids, and structure integrity. Specifically, the impact echo is more inclined to provide info on structure integrity and condition as well as map some of the larger voids in a concrete structure. The Radar method is used to verify and map the locations of the reinforcements and possibly map voids or honeycomb.

The seismic approach

The seismic (acoustic) method is based on the measurement of the vibration response of a medium to an excited impact or vibration source. The seismic wave propagation is governed by the wave equation with the appropriate boundary conditions. The application of boundary conditions depends on the location of the boundary with respect to the location and frequency content of the source. Though most solids posses elastic properties of wave propagation, the elastic behavior is usually approximated by the simpler acoustic one in the analysis stage. The acoustic wave equation provides all the kinematic and dynamic accuracy needed to map the seismic wave propagation in most media.

One NDT method that relies on measuring vibrations is the Impact Echo (IE) method. The applications of the IE technique include: determining both the thickness and flaws in plate-like structure members, such as slabs, walls; detecting flaws in beams, columns and hollow cylindrical structural members; assessing the quality of bond in overlays; and detecting void in post tension tendon duct etc. One of its main advantages is that it can detect flaw locations as well as the flaw depth. The popularity of this technique has been augmented by well published comprehensive research done by the developers of this technique (i.e. Asano et. al., 2003).

Acoustic methods provide one of the best penetration capabilities out there. The lower frequencies, necessary for the better penetration, along with the slower wave speed, provide the reasonably short wavelengths necessary to resolve small anomalies. The speed of acoustic waves (used in the Impact echo) is far slower than electro magnetic waves (used in the radar). Despite that we have higher frequencies in the radar, because of the slow velocity of IE, the resultant resolution is reasonably high in the IE.

Radar Survey

Ground Penetrating Radar (GPR) is a nondestructive method that produces a continuous cross-sectional profile or record of a bodies features, without drilling, probing, or digging. GPR uses electromagnetic wave propagation and scattering to image, locate and quantitatively identify changes in electrical and magnetic properties in the ground. Detect ability of a subsurface feature depends upon contrast in electrical and magnetic properties, and the geometric relationship with the antenna.

Radar is analogous to the pulse-echo technique using electromagnetic waves (radio waves or microwaves). In civil engineering applications, inspection depths are relatively shallow and only short pulses of electromagnetic waves (microwaves) are used. For this reason, the technique is often called short-pulse radar, impulse radar, or ground penetrating radar (GPR).

Radar survey has been successfully used to locate reinforcing bars and post-tensioning tendons, to estimate the thickness of slab, wall, pavement and more recently to locate and identify concrete anomalies and deterioration (i.e. moisture variations, delamination, honeycombing or fractures).

The most attractive features of this technique are its ability to scan a large area under investigation in a short time; its high sensitivity to subsurface moisture and embedded metal; its capability to detect both metallic and non-metallic objects. Specifically, the speed of the radar waves allows for continuous rolling acquisition and better cross section plots not possible at the same level with seismic methods.

THE LIMITS

The practical limits on resolution of images from seismic or radar (electromagnetic) data depend on the spectrum of the source pulse, the incompleteness of the recording geometry, and the fidelity with which one can model the reference medium. These factors together prevent one from recovering a point image from data produced by a point diffractor in a given body.

To test the limits of resolution in recovering a point diffractor in the seismic case, I create a model simulating a concrete slab with unlimited thickness (half space) and a diffractor located at a depth of 0.5 meters from the recording surface The source pulse as shown in Figure 1 has a peak frequency of 110 MHz (The high frequency is necessary to simulate radar behavior as well, later we will show the case of lower acoustic frequencies).

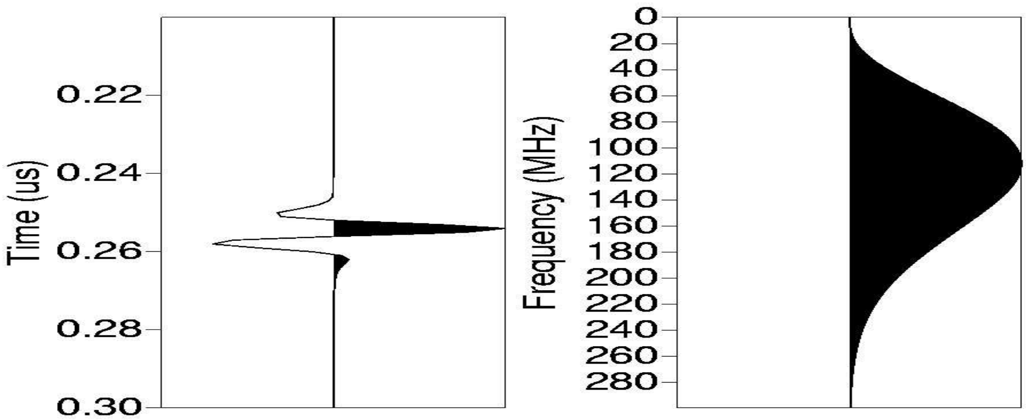

Figure 1: The source pulse (left) and its frequency content (right). The source pulse has a peak frequency of 110 MHz.

The acquisition is done by moving the source and receiver simultaneously with an offset of 0.2 meters between them, which is similar to what is done in radar acquisition and sometimes in seismic acquisition. Figure 2 shows a section in which a reading is taken every 2 cm starting from the origin at 0 to a distance of 2.4 meters. The diffractor is clearly located in the middle at about 1.15 m. With this recording range and sampling, we notice that we will not be able to image all the energy scattered by the diffractor and we probably under sampled the deeper flanks of the diffraction moveout. The under sampling is usually avoided in radar acquisition with the usual high scan rate provided by the speedy acquisition of radar data. Such a feature is not available in seismic data unless one puts the extra effort to acquire finely sampled data.

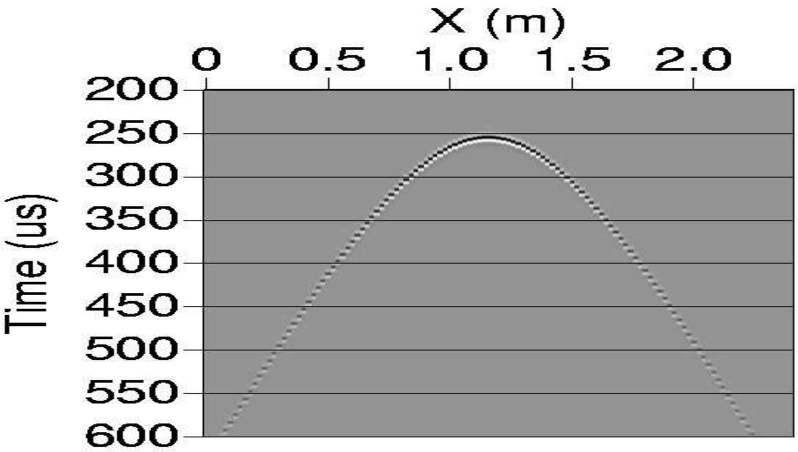

Figure 2: A section through the diffractor with a sampling of 2 cm and an offset between the source and receiver of 20 cm.

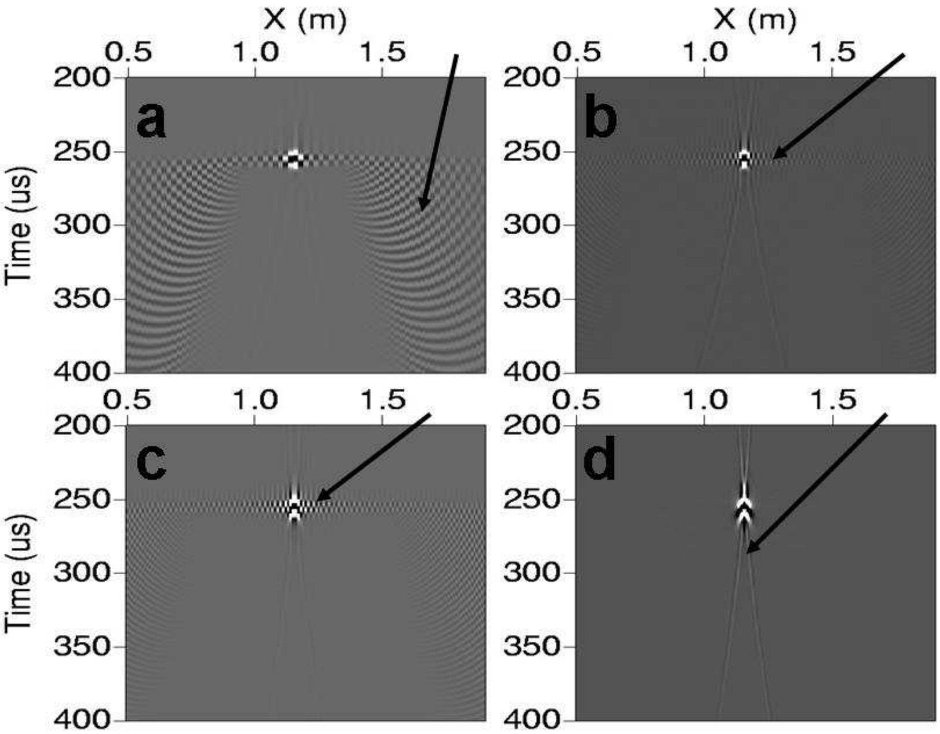

Figure 3: The recovered image using zero-offset migration applied to (a) the synthetic data of a diffractor in Figure 2, (b) a similar synthetic data with twice the sampling points (sampling interval of 1 cm) in the lateral direction, (c) a similar synthetic data but with the same sampling interval as in (b) but twice the lateral range, and (d) a similar synthetic data with the larger range as in (c), but with double the sampling points (sampling interval of 0.5 cm).

We next migrate the data to map all recorded energy back to its scattering point. In the migration we will use the true velocity of the medium of 4000 m/s. In perfect conditions, with extra fine sampling, a large recoding range and a broadband wavelet we should obtain a near perfect pulse. However, the recording and sampling limitation will prevent obtaining a perfect pulse. Figure 3 shows the migrated image and we clearly observe some sort of leakage of energy in all cases, more so for the coarser gridding case and limited recording range. In Figure 3a the recording sampling interval was 2 cm and the recording range as shown in Figure 2 spanned from zero to 2.4 meters. Not only does the image not represent a perfect pulse but clear dispersion appears in the area given by the arrow. In Figure 3b we doubled the sampling rate while keeping with the original recording range. We at least managed to reduce the dispersion. One way to investigate the pulses resolution is to closely look at its spectrum.

Figure 4 shows the spectrum response of the four images in Figure 3. Figure 4d provides the closest spectrum to a pulse as the frequency range is confined to the diffractor location and spans many frequencies. This result corresponds, as expected, to the acquisition with the largest lateral range and finest sampling. Yet, the result, as expected, did not provide a perfect pulse. In fact, it is practically impossible to recover a perfect pulse with finite acquisition parameters. We can, at least, hope to get as close as possible to that by broadening the frequency range, expanding the acquisition surface, and decreasing the sampling interval.

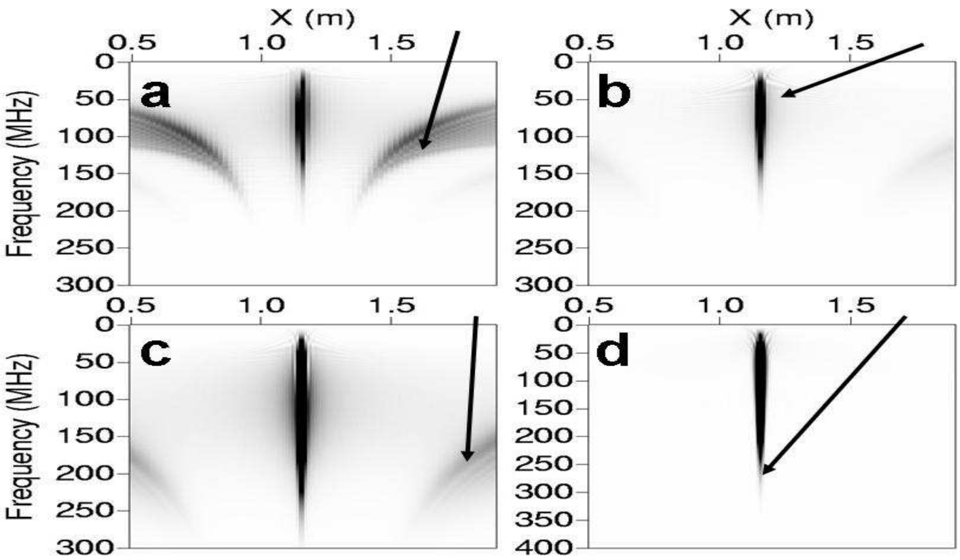

Figure 4: The frequency spectrum of the images shown in Figure 3. The arrows point to features discussed in the text.

THE RAYLEIGH CRITERION

Although thin-void response is made clearer and less confusing by broad frequency band data, the fact is that measuring the thinness of a thin void is not a question of frequency bandwidth. The basic problem is that the wave-length of the signal must be similar in dimension to that of

the void. If it is much longer than the void, the determination of interference or phase shift is less reliable and with increasing length becomes impossible. If it is much shorter. the problem is not one of a thin void. The thin-void problem assumes that the void (crack) is thin compared to the dominant wavelength of the wavelet. To demonstrate that the thin void problem is not a question of frequency bandwidth. remember that soap film thicknesses are measured using monochromatic light and principles of interference (see, e.g., Sears, 1958). The seismic (radar) thin-void problem can be approached from the same stance. An advantage of having broad-band data is that interference problems are less disruptive. If the concern were only the resolution of isolated thin voids, broad-band data would not be needed.

The Rayleigh criterion states that the resolution limit of a reflection is $\gamma/4$, where γ is wavelength. It is derived from optics and more detail can be found in any good book on the subject, for instance, Sears (1958). Ricker (1953) refined this limit slightly for closely spaced reflectors of equal strength and polarity. Widess (1973) extended this limit to γ/8 for reflectors of equal strength and opposite polarity. The weakness of the Ricker and Widess criteria is that they are based on models, and application is restricted to situations that approximate the models.

For isolated thin voids, reflections from the top and bottom of the void interfere. The result is a single wavelet response which approximates the time derivative of the original wavelet. A synthetic example is given next.

THE IMPACT ECHO EXAMPLE

The Impact echo (IE) approach uses seismic waves but instead of looking at reflections in the time domain we look at resonance frequencies in the frequency domain. Thus, we end up using lower frequencies for IE applications. Here we numerically model a Slab using acoustic waves and observe results of an IE simulated experiment on synthetic data. Of course, computer modeling will never include all the elements and conditions faced in the field but at least it will give us an indication of what is possible and what is impossible in resolving the IE data. Real test may include conditions not included in this model, but this experiment will at least point out the limits.

Figure 5 shows a model of acoustic velocities used to generate the acoustic wave propagation using finite difference applied to the acoustic wave equation. The source and receiver location given by the green dot is above the modeled void. In this model we vary the thickness of the void and compare results. In the last test, we remove the void altogether and generate void less synthetic data. The model includes reinforcement near the top of the slab as well as a thin lower velocity layer.

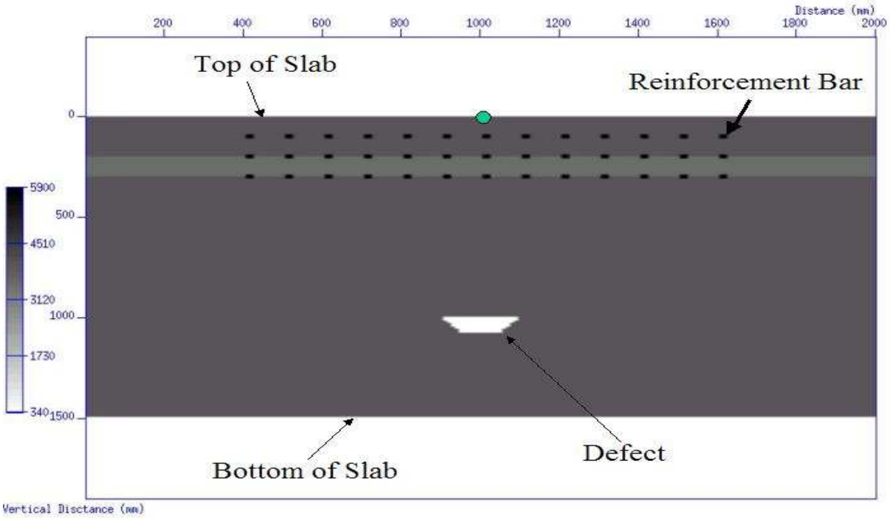

Figure 5: An acoustic velocity model of the Slab used to numerically generate acoustic waves similar to those used in the IE test. The point in the middle is the location of the acquisition of IE in Figure 6.

Acoustic waves usually do not have the penetration limitations that Radar data have and thus provide results from deeper regions. Figure 6 shows the spectrum response of the acquired traces for the different models with different void thicknesses. The void less model with spectrum shown on the right has three dominant peaks corresponding to the bottom of the slab. Other smaller peaks could be the result of reflections from the edge of our model. The three peaks are at 1.35 KHz, 2.75 KHz and 4.05 KHz, which are the first, second and third mode of resonance from the bottom of the Slab and suggests the actual length of 1.5 m.

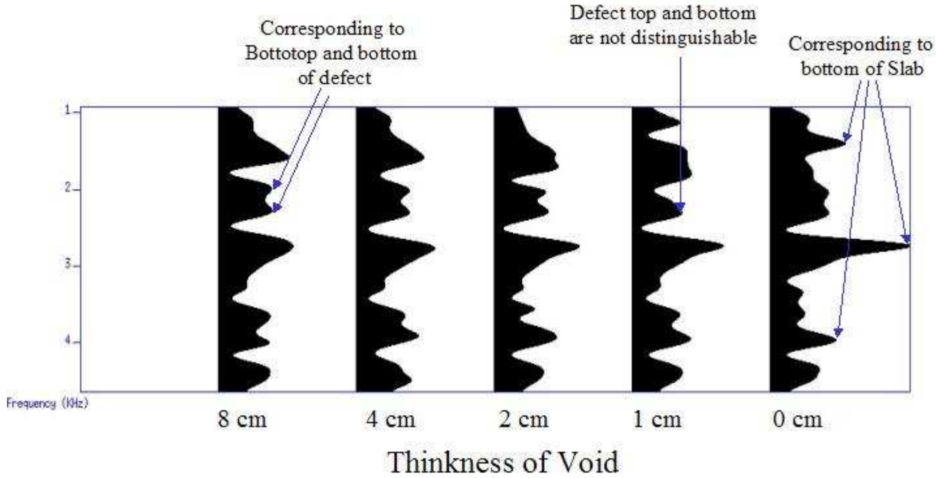

Figure 6: The spectrum response of the measured acoustic trace for various thickness of the void.

The model with the thick void (8 cm) having the spectrum shown in Figure 6 (left) has additional peaks corresponding to the void. Actually one peak corresponding to the top and another corresponding to the bottom of the void. The peaks corresponding to the bottom of the slab is less sharp and has lower amplitude than the void less case. As the thickness of the void decreases the sharper the peaks corresponding to the bottom of the slab become and in the case of the 1 cm void thickness model we can not distinguish between the top and bottom of the defect reflections. They have practically the same peak. This complies well with the Rayleigh criterion discussed earlier.

THE SEISMIC-RADAR DIFFERENCE

A major difference between seismic and electromagnetic waves is the speed of wave propagation for different materials. For example, electomagnatic waves travel the fastest in Air (light speed), while seismic waves travels the slowest in Air (Sound speed). Thus, air filled voids appear differently on seismic sections versus electromagnetic ones. Also, electromagantic waves travel slowly in water, much slower than air. On the other hand, seismic waves though travel slowly in water but much faster than in Air. These differences will help in distinguishing the medium of propagation from the acquired data.

Here, we again numerically model a medium resembling a 0.7 meters thick Concrete Slab with a layer of rebar on the upper side and air filled voids below. Figure 7 shows the model with velocities for seismic waves. The voids have seismic velocities of 0.3 m/ms and are given in white, while the concrete velocity is set to 4 m/ms. The metal reinforcement has a velocity of 5.9 m/ms.

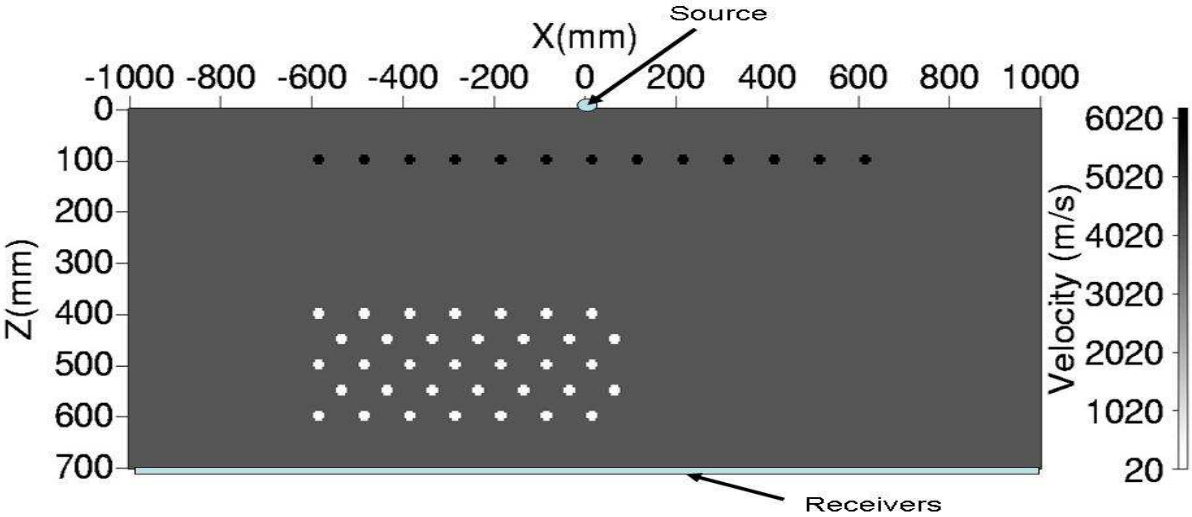

Figure 7: A model emulating a concrete slab with reinforcement towards the top and air-filled voids towards the bottom. The source is located on the middle of the top surface and the receivers are located along the whole model on the bottom. The model is given in terms of seismic velocities.

Using finite difference applied to the wave equation for a source located on the top surface and receivers located on the bottom surface expanding through the whole model laterally, we obtain the synthetic section shown in Figure 8. The peak frequency of the source is 13.5 KHz. Clearly, the voids have altered the shape of the wavefront. In the voids area, we have both a dispersion of the energy and a delay in the first arrival caused by the lower velocity of the voids.

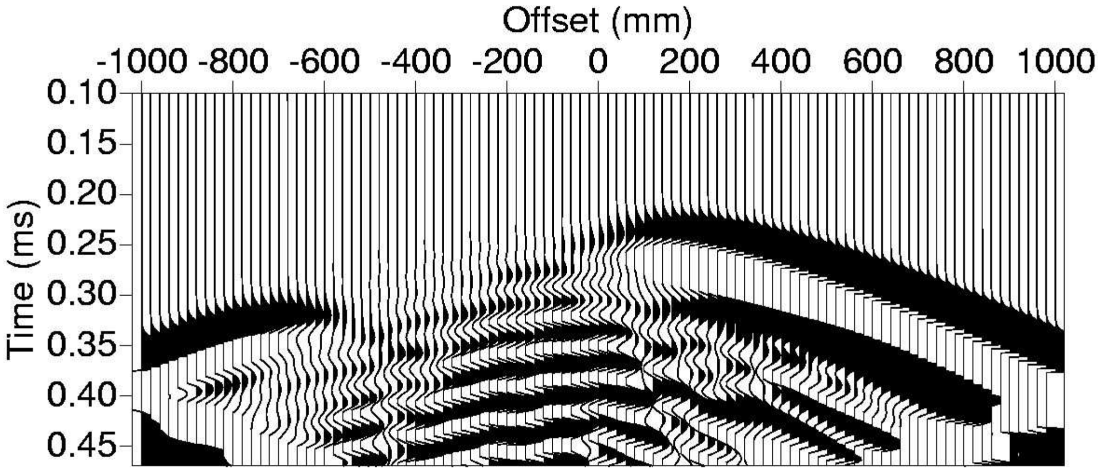

Figure 8: The synthetic section corresponding to an excitation of a source pulse with peak frequency of 13.5 KHz in the model shown in Figure 7.

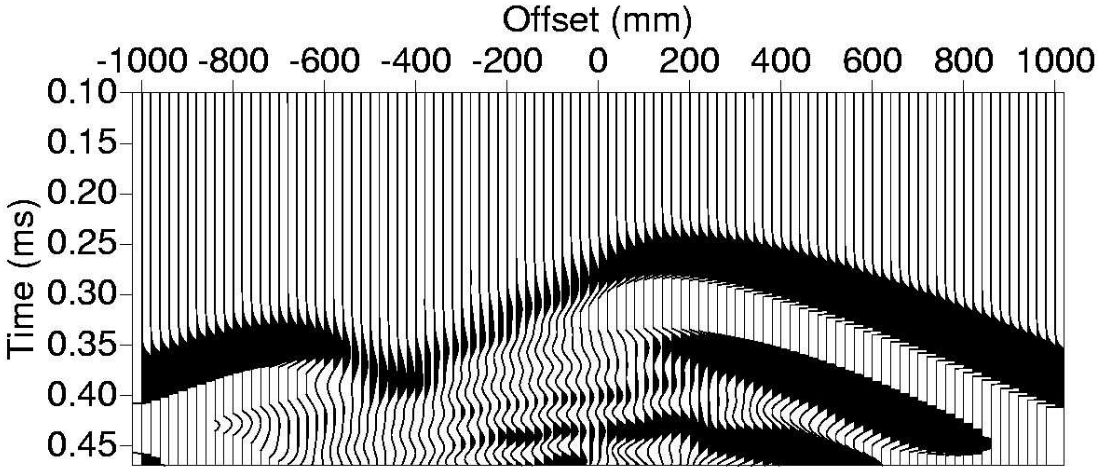

Figure 9: The synthetic section corresponding to an excitation of a source pulse with peak frequency of 9.3 KHz for in model shown in Figure 7.

Figure 9 shows the same synthetic section as in Figure 8 but with a lower source peak frequency of 9.3 KHz. The dispersion with this lower source frequency is less however, the first arrival delay phenomena is similar.

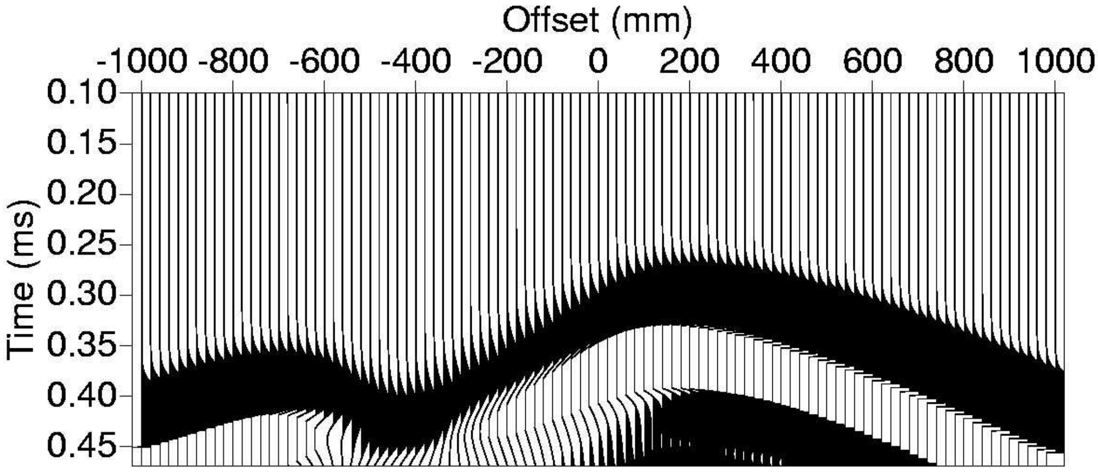

Figure 10: The synthetic section corresponding to an excitation of a source pulse with peak frequency of 6.5 KHz in the model shown in Figure 7.

Finally, Figure 10 shows the same synthetic section as in Figure 8 but with an even lower source peak frequency of 6.5 KHz. The dispersion with the lower frequency is less than both examples above, however, the first arrival delay phenomena is again similar. Thus, for seismic waves the voids manifest them selves as a clear delay in arrival caused by much lower than average velocity usually associated with air-filled voids. The dispersion of the wave reduces at lower frequencies since the wavelengths associated with the lower frequencies are much larger than the void dimensions as reflected by the Rayleigh criterion.

Using the same model in Figure 7, we numerical model the propagation of electromagnetic waves. The wave velocity of the modelled material is different and given by Figure 11.

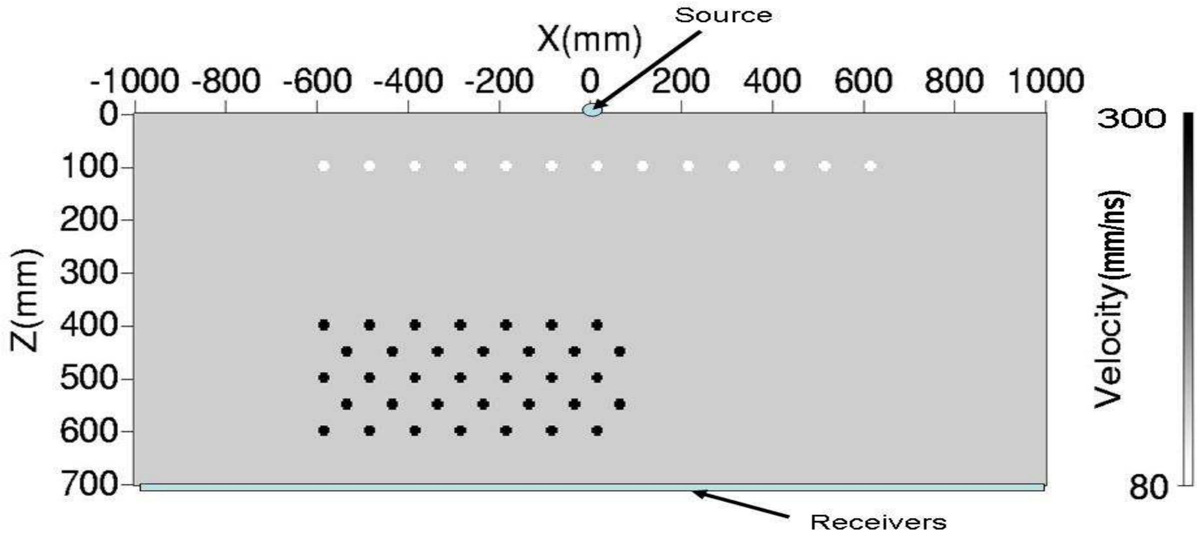

Figure 11: A model emulating a concrete slab with reinforcement towards the top and air-filled voids towards the bottom. The source is located on the middle of the top surface and the receivers are located along the whole model on the bottom. The velocities here of the materials are for electromagnetic waves.

Again, using finite difference applied to Maxwell's equations for a source located on the top surface and receivers located on the bottom surface expanding through the whole model laterally, we obtain the synthetic section shown in Figure 12. The peak frequency of the source is 1.4 GHz. The voids have altered the shape of the wavefront slightly (less than in the seismic case). In the voids area, we have both a loss of high frequency energy and slightly faster first arrival caused by the higher electromagnetic wave velocity of the voids. This is clearly observable by concentrating on the arrows size and location in Figure 12.

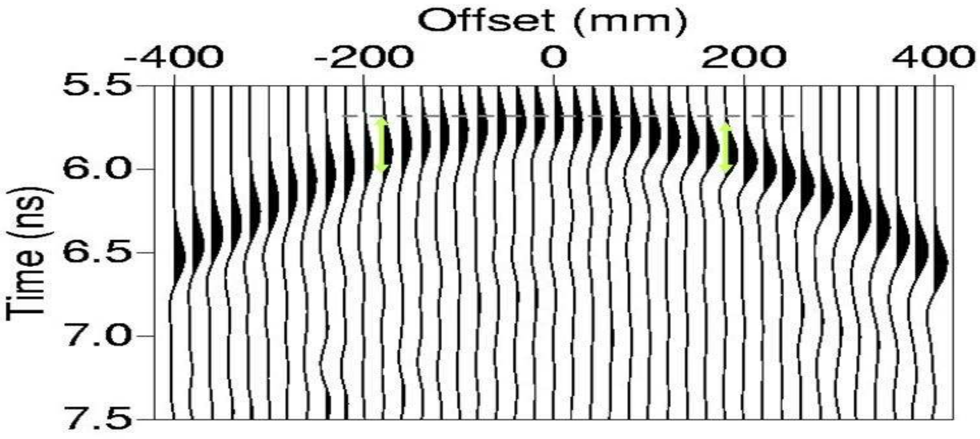

Figure 12: The synthetic section corresponding to an excitation of a source pulse with peak frequency of 1.4 GHz in the model shown in Figure 11. The arrows clarify the time length of the wave and its time location.

Using lower pulse frequencies as shown in Figure 13, reduces the dispersion and faster arrival features observed clearly in Figure 12. The reason is that with this typical antenna frequency for radar waves, the wavelength is comparably large. Specifically, the 800 MHz radar wave has a wavelength of about 163 mm, which nearly covers the full void area. For comparison, the wavelength of the lowest seismic frequency of 6.5 KHz is 615 mm. However, seismic waves are influenced by voids far more the radar waves.

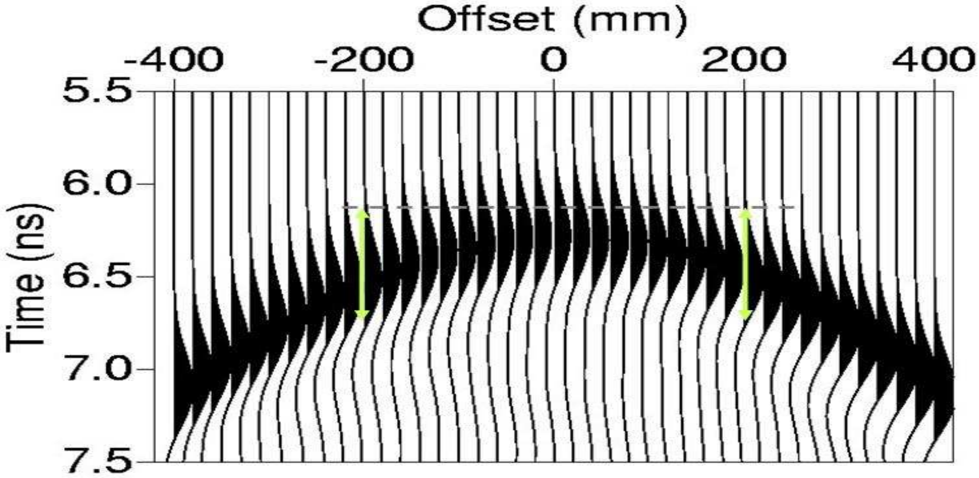

Figure 13: The synthetic section corresponding to an excitation of a source pulse with peak frequency of 0.8 GHz in the model shown in Figure 11. The arrows clarify the time length of the wave and its time location.

A PHYSICAL TESTAMENT

We acquired radar data using an 800 MHz Radar over a 1.5 meter thickness concrete slab shown in Figure 14. Dense reinforcement is present at the top and bottom end of the slab. However, the Slab contained voids and honeycombs in some regions. The frequency spectrum of the source signal provided enough energy to penetrate down to the Slab bottom.

Figure 14: A picture taken of the side of the exposed Slab which clearly displays a sample of the reinforcement configuration. The slabe is 1.5 meters thick.

Figure 15 shows a section from the radar profile over the slab. The profile extended the length of the slab of 32 meters. Numerous reflections appear in the profile including reflections from the top three layers of reinforcement given by arrows (4), (5), and (6). However, arrow (7) points to a location in which reflections have lower frequency content and have earlier arrivals. This phenomenon is caused by the presence of honey combs and voids above these reflections resulting in wave features similar to those observed in Figure 12.

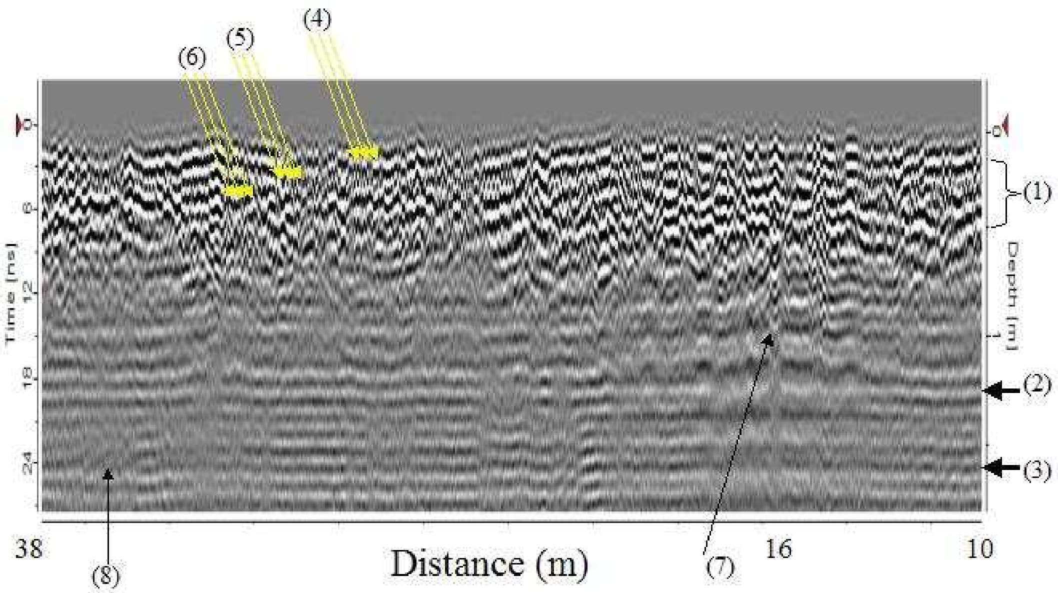

Figure 15: An actual radar Profile of about 32 meters long from the top of a thick Slab (1.5 m) with some features apparent in (1) an area containing reflections from the top reinforcement bars, (2) reflection from the bottom reinforcement (lower resolution), (3) reflection from the bottom of the Slab at 1.5 meters, (4) reflections from individual bars of the shallowest part of the top reinforcement, (5) reflections from middle part of the top reinforcement, and (6) reflections from the bottom of the top reinforcement. The arrow (7) points to reflections with lower frequency content and a slight pull up that is caused by the presence of voidsabove it. The arrow shows a similar phenomena but at a lower extent.

CONCLUSION

Resolution, a critical attribute in NDT applications, controls our ability to interpret various anomalies on seismic and radar data. Seismic and radar waves are kinematically similar, thus, they are governed generally by the same resolution limits. However, seismic and radar data differ in how they are acquired and how they respond to different materials. Seismic waves are far more sensitive to air-filled voids, which are the most sought after anomaly in NDT investigations, than electromagnetic (radar) waves.

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