Near-Field Effects on Direct-S Radiation Patterns

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Introduction

Real-data measurements of direct-S first arrivals produced by vertical-force sources imply S-wave radiation patterns in real-earth media differ from the idealized S-wave radiation patterns developed with mathematical theory, and also differ from many assumptions used in numerical modeling of S-wave propagation. This paper presents real-data measurements that support this statement and provides evidence showing that relatively minor azimuthal variations in the near-field medium immediately surrounding a seismic source station may be the cause of large-scale azimuth-dependent irregularities observed in S-wave illumination patterns when receivers are positioned at far-field distances. The evidence presented in this material concentrates on S-wave radiation produced by explosive sources. It is logical to extend the results to any source that radiates SV displacements in all azimuth directions in the manner that explosive sources do. Such a logical extension extends the principles presented here to vertical vibrators, vertical impact sources, and any type of vertical-force source.

Early Investigations

A considerable amount of research was done in the 1950's and 1960's to understand S-wave radiation generated by explosive sources. This time frame was the period when there was world-wide tension over the issue of developing and testing nuclear explosive devices. The impetus for these S-wave radiation studies was the desire to determine if the presence of SH shear modes in large-scale seismic events was a definitive way to segregate natural earth seismicity from seismic events produced by underground explosions. Several agencies in various countries pursued these S-wave radiation studies with the objective of developing technology that would recognize when violations of nuclear test ban treaties occurred.

Fundamental premises of this research were: (1) the observation that naturally occurring earthquakes created robust SH motion, and (2) the assumption that man-made explosions should not generate SH shear modes. The logic of these two premises was based on the assumption that an explosion caused constant-amplitude SV-mode displacements to radiate in all azimuth directions. Uniform-amplitude and opposite-azimuth SV displacements should not generate SH motion when their responses are recorded by a transverse horizontal sensor because a transverse geophone sums the two responses and records a value of zero if the two opposite-azimuth SV displacements are indeed equal amplitude. Such a conclusion is not true when opposite-azimuth SV displacements are recorded by a 3D array of sensors around a source station and SV events recorded in opposite-azimuth directions can be subtracted rather than added.

Controversy and puzzlement arose when real-data observations showed SH modes were consistently observed at receiver stations when explosive sources were fired. Thus the presence of SH data in large-scale seismic events recorded at isolated sensor stations at widely separated global stations did not distinguish earthquakes from massive explosions as was anticipated.

The only early studies on the subject of SH radiation patterns generated by explosives that have been found in geophysical literature were published by scientists doing investigations in Britain and in the United States of America. Other pertinent publications may be in other public sources, but no effort has been made to search any source except peer-reviewed geophysical publications. The purpose of this EGL paper is to present the conclusions reached in only a few reputable studies, not to present a comprehensive review of all published studies on the topic of SH radiation from explosive sources. Following several years of field tests by different groups, the conclusions reached by investigators is well summarized by the following quotes:

1. Hundreds of 3C records testify that explosions generate prominent SH motion (Kisslinger et al., 1961).

2. On no occasion has an underground firing failed to give rise to significant transverse waves (Wright and Carpenter, 1962).

Field tests involved explosions of different magnitudes, and source-receiver offsets ranged from short to long distances. Of particular interest to geophysicists engaged in reflection seismology, many tests involved small buried charges of less than 1 kg and short travel paths of only 20 to 100 m. Tests were done in many media ranging from loose soils to hard rocks. It is important to note that test data were acquired with analog equipment because no digital seismic recording systems were available during the time span when these tests were done.

One interesting test result published by Wright and Carpenter (1962) is illustrated in Figure 1. These researchers placed small explosive charges weighing less than 2 ozs (57 gms) in the most homogeneous medium they could fabricate. Specifically, the medium surrounding their explosive charges was soft modeling clay that was kneaded into a large sphere around the explosive material. Great care was taken to ensure there were no observable interfaces or voids at the explosive-clay interface or anywhere within the clay medium. The objective was to form a seemingly perfect homogeneous seismic propagation medium that was in perfect contact with an explosive charge. After the explosive was detonated, a plaster cast of the explosion cavity was made to illustrate the geometrical shape of the cavity. Horizontal cross-sections through two of these plaster casts are shown in Figure 1.

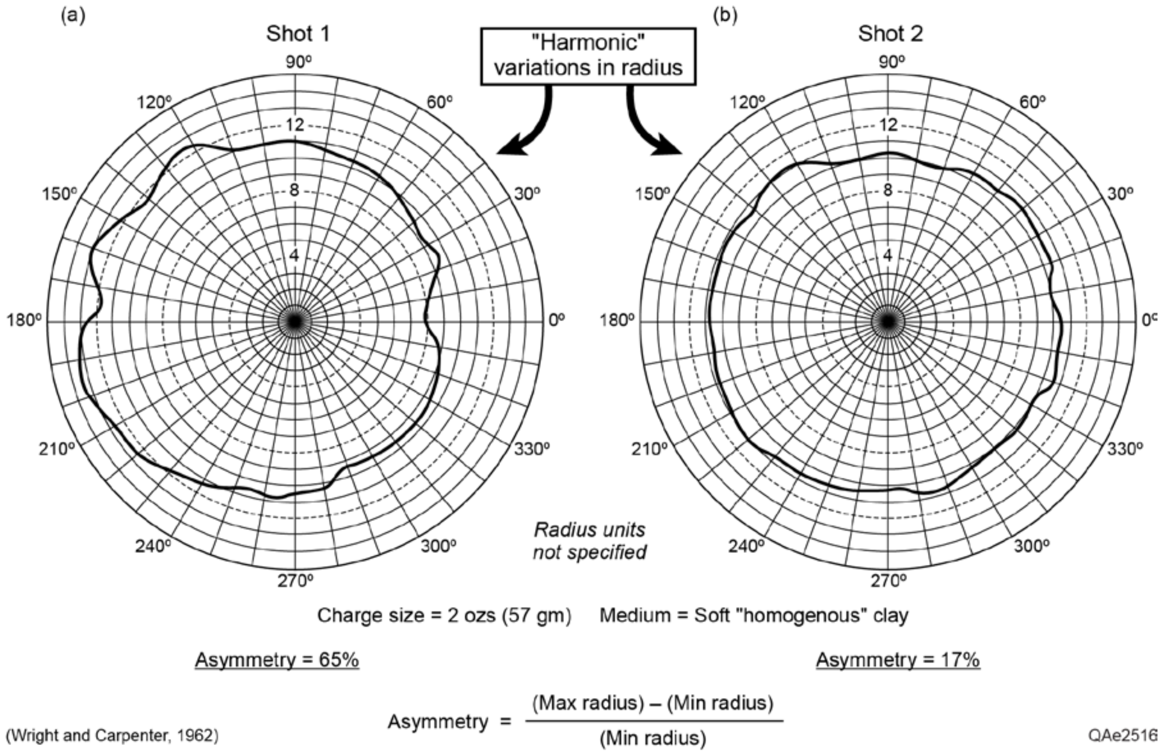

Figure 1. Horizontal cross-section cuts through plaster casts of explosion cavities created when a small explosive was detonated in homogeneous modeling clay. (a) High asymmetry cavity shape (strong shearing created). (b) Moderate asymmetry cavity shape (moderate shearing created). Reproduced from Wright and Carpenter (1962).

A fundamental principle illustrated by these plaster-cast depictions of explosive cavity shapes is that in spite of diligent efforts to create a perfect homogeneous medium around an explosive shot, the explosion cavity is always asymmetrical and never a perfect circle. This asymmetrical cavity shape indicates a shearing motion is applied to the propagation medium. The asymmetry parameter assigned to each cross-sectional view in Figure 1 is added by the author of this paper (Hardage) and was not proposed by Wright and Carpenter, the researchers who did the work. If a cavity is a perfect circle in map view, this asymmetry parameter would be zero.

Wright and Carpenter (1962) introduced the term “harmonic” variations labeled on Figure 1 to describe the cavity shapes they observed. They used this term “harmonic” to indicate the nature of the variations in cavity radius that were created in their tests. They apparently were attracted to this terminology because of earlier work done by Taylor (1950) and Lewis (1950), whom they referenced. These two preceding researchers (Taylor and Lewis) from the 1950’s decade cooperated to produce an informative 2-part research study that illustrated the inability to avoid the creation of shearing motion whenever exploding gases expand. Taylor (1950) published the first part of the research as a mathematical study. His mathematical model demonstrated that whenever one fluid accelerates to displace a second fluid, any minute irregularity in the interface separating the two fluids grows in magnitude as a hyperbolic cosine shape. The fundamental variable embedded in this hyperbolic cosine function is the square root of the difference between the two fluid densities. Taylor's mathematical model is illustrated by the flow chart presented on Figure 2.

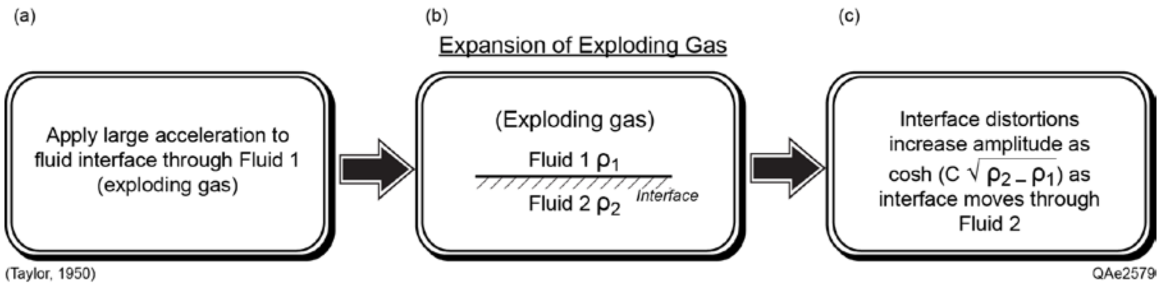

Figure 2. Mathematical description of shearing motions that result when exploding gases expand. (a) Fluid 1 (having a density ρ_1) accelerates to displace fluid 2 (having density ρ_2). (b) The interface between the two fluids defines the boundary of exploding gases, which are fluid 1 above the 2-fluid interface. (c) Any distortion away from a perfectly flat interface grows in amplitude as a hyperbolic cosine shape with the amplitude of the hyperbolic cosine controlled by the square root of the difference of the two fluid densities. Summarized from Taylor (1950).

Lewis (1950) verified the theory developed by Taylor by constructing an elaborate apparatus that allowed compressed air to accelerate and displace a second fluid (which was suspended water at rest). The expanding compressed air simulated the expanding gases produced by an explosive (Fig. 2b). The suspended water represented a homogeneous medium attempting to contain this expanding gas. The concept used to "suspend" the water so that it was not constrained by a rigid barrier at its base was ingenious, but will not be discussed. Lewis then recorded high-speed photographs that showed how the two-fluid interface was distorted as a result of the acceleration of the expanding gas. In the first series of tests, the fluid interface was deliberately disturbed immediately before the onset of fluid-2 acceleration by the expanding gases. The four panels in Figure 3 are redrawn versions of the high-speed photographs Lewis acquired to document the interface movement when it was positively known there were small irregularities in the propagation medium in the near-field region of the propagation medium.

As the expanding gas pushed the interface farther from its original position (Fig. 3a,3b,3c), the small interface irregularities produced by the mechanical paddle continually grew in amplitude and eventually assumed deep-cavity shapes that were reasonable approximations of a hyperbolic cosine function (Fig. 3d). This behavior is experimental evidence that Taylor's theory (Fig. 2) is a good approximation to the shearing action that expanding explosive gases produce as they displace a medium immediately surrounding an explosive source.

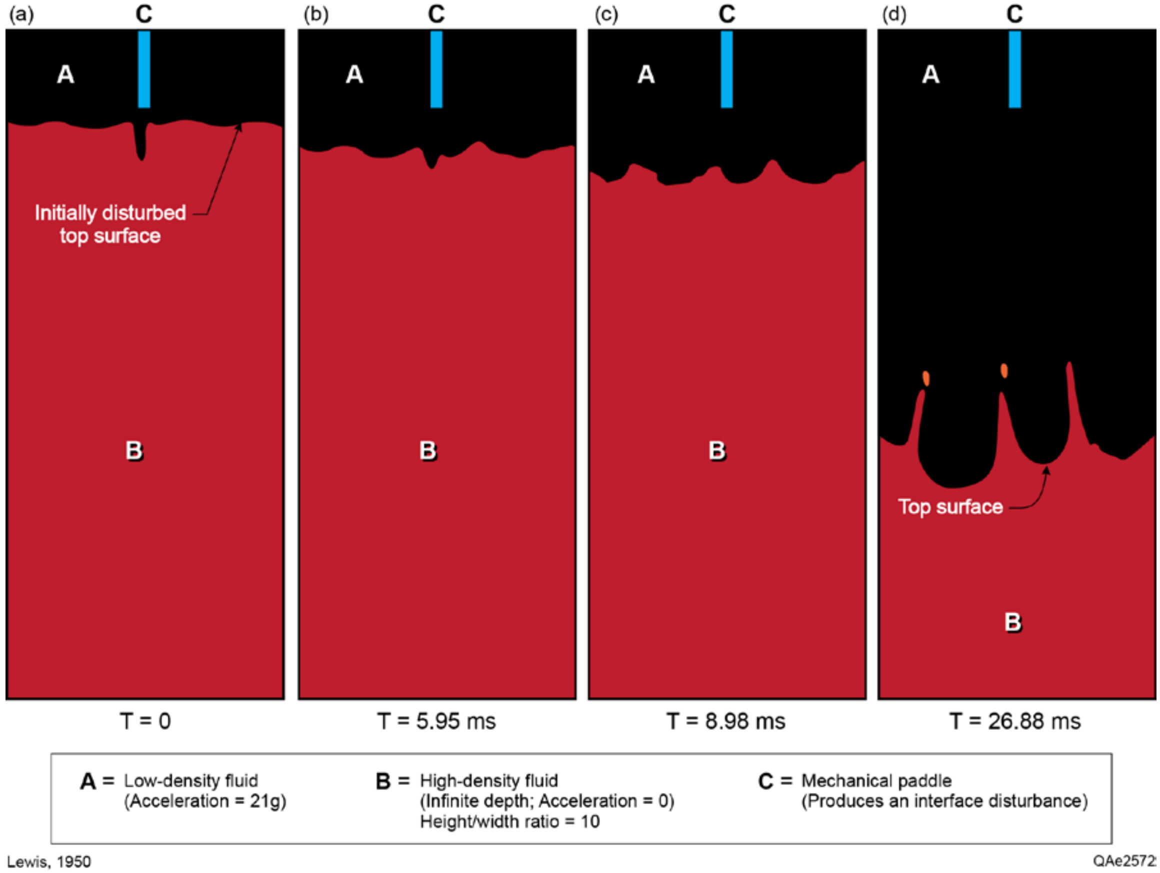

Figure 3. Redrawn versions of high-speed photographs of interface distortions that result when a light-density fluid **A** is accelerated to displace a heavy-density fluid **B**. **A** is compressed air that simulates rapidly expanding explosive gases. **B** is suspended water at rest with no rigid constraint at its base. A mechanical paddle creates an interface disturbance immediately before volume **A** begins its acceleration (a). These small amplitude interface distortions grow in magnitude as the expanding gas displaces the heavier fluid (b,c,d). As the exploding gases expand, the initial small-amplitude interface disturbances look more and more like large-amplitude hyperbolic cosine functions (d). Modified from Lewis (1950).

Additional tests were then done in which extra precaution was taken to not create any type of interface irregularities before the expanding gas began to accelerate. The interface behavior in this “perfect interface” situation is documented in Figure 4. In all tests, the interface separating the expanding gasses and its surrounding medium developed deep-cavity distortions that were almost identical to the distortions that occurred when there were deliberate efforts to create interface distortions before explosion detonation was initiated. In spite of efforts to ensure the fluid interface was not distorted in any way before the expanding gases began to accelerate, large irregularities always appeared in the propagation medium at the exploding gas interface.

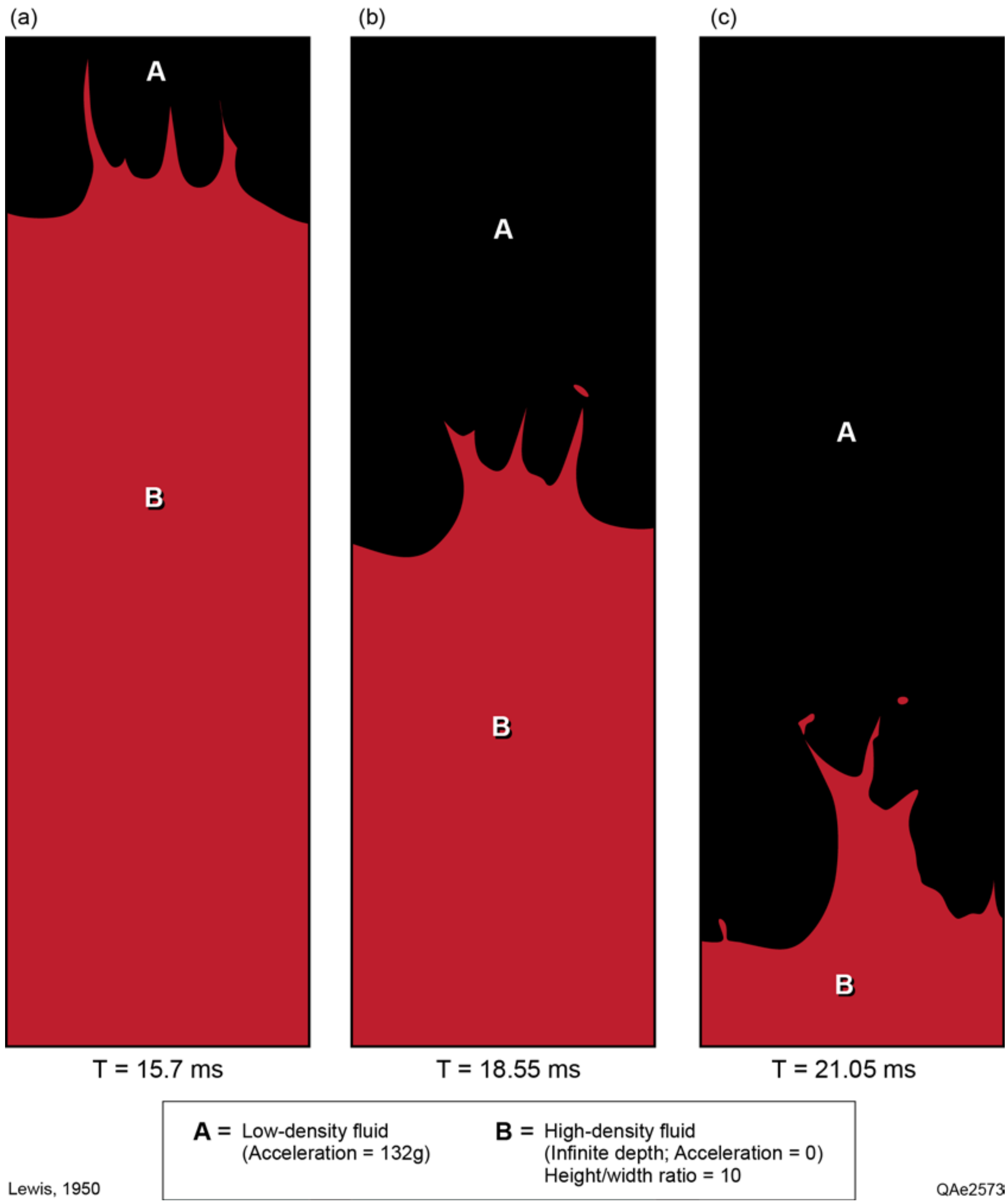

Figure 4. Redrawn versions of high-speed photographs of interface distortions that result when a light-density fluid **A** is accelerated to displace a heavy-density fluid **B**. **A** is compressed air that simulates rapidly expanding explosive gases. **B** is suspended water at rest with no rigid constraint at its base. Although no mechanical disturbance of the interface is allowed, interface distortions still appear and grow in magnitude as the expanding gas displaces the heavier fluid (a,b,c). As the exploding gases push the interface farther, the interface disturbances look more and more like the hyperbolic cosine functions predicted by Taylor (1950). Modified from Lewis (1950).

Real World Near-Field Conditions at Seismic Source Stations

A fundamental principle established by the research of Taylor (1950), Lewis (1950), and Wright and Carpenter (1962) is that it is apparently impossible for exploding gases to expand without causing asymmetrical shear distortion in the medium that surrounds the source of the exploding gas. These asymmetries cause shot-hole explosives to create SH modes in addition to their fundamental full-azimuth SV modes. This interface distortion occurs even when the surrounding medium is perfectly homogeneous (water in Lewis's test) or is as homogeneous as can be created with modeling clay (work of Wright and Carpenter). A logical extension of this 1950's to 1960's research to today's EGL direct-S research is that, in real-earth seismic data acquisition, we must assume there can never be a constant-amplitude radiation of SV displacements in all azimuth directions around any source used to generate S waves.

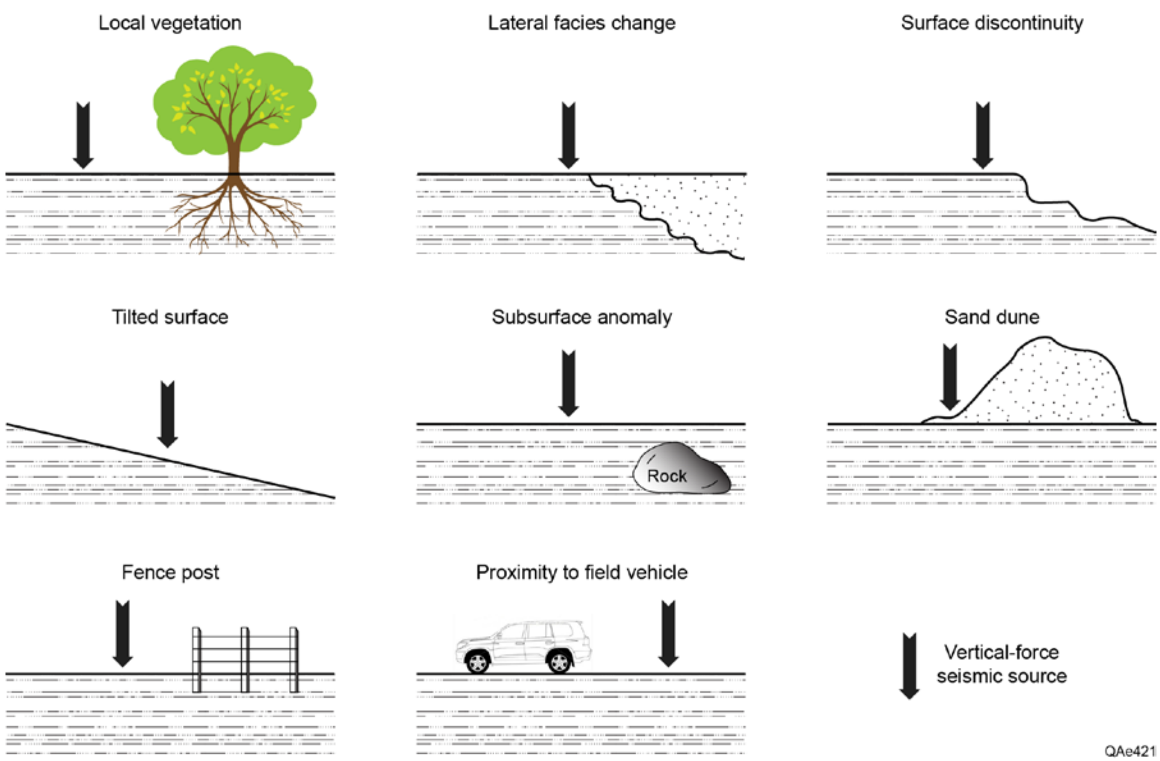

Figure 5. Examples of real-world anomalies that exist in the near-field region of a source station. Each of these anomalies can create the near-field shearing action photographed by Lewis (Fig. 3 and 4).

The fact that minute variations in the immediate near-field of a source station cause large variations in the far-field region of the propagation medium (Lewis, 1950) means that minor, easily ignored discontinuities in the medium immediately surrounding a vertical-force source can cause significant amounts of shearing action to propagate away from a source station. Common examples of the discontinuities that exist at essentially all seismic source stations in the real world are illustrated in Figure 5. These types of near-field anomalies cause the SH-mode generation documented by Taylor, Lewis, Wright and Carpenter to occur not only for explosive sources, but for any vertical-force source that can be envisioned as creating uniform SV shear displacements in all 360 degrees of azimuth around a source station. Thus the early 1950's to 1960's work summarized here provides compelling evidence that all vertical-force sources will produce SH shear modes in essentially any geologic environment.

Conclusions

We do better research if we stand on the shoulders of those who precede us and use their research findings to explain and expedite the research activities we pursue today. The approaches used in the 1950's and 1960's to determine if explosives generate SH shear waves are elegant in the sense that researchers did not have computational resources to do elaborate numerical modeling, but had to do physical measurements to understand and explain the seismic wave physics they observed. We at the Exploration Geophysics Laboratory also attempt to use physical measurements to develop the principles of direct-S physics of vertical-force sources that we now promote, but we supplement these physical tests and measurements with a reasonable amount of numerical modeling. EGL needs to step back from time to time and consider if we have the proper balance between real-world data tests and numerical modeling. These two approaches – real data measurements and numerical modeling – are complementary and are essential in rigorous research, but either approach can be over emphasized.

It is proper to extend the conclusions reached in these early investigations of direct-S waves produced by explosive sources to vertical vibrators, vertical impacts, and all vertical-force sources. The reason for doing these early tests was the dilemma that came to researchers when they observed SH data propagating away from an explosive shot and tried to envision how a source that supposedly produces a uniform radiation of radial SV displacements in all azimuth directions around a source station can ever generate SH data. Thus the problem that they investigated applies to any source that produce a 360-degree azimuth radiation of SV displacements. That category of sources includes vertical vibrators and vertical impacts as well as shot-hole explosives.

EGL offers this paper to our sponsors to provide insight into the physical mechanisms by which SH modes are produced by vertical-force sources.

References

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