geoconvention
Calgary • Canada • May 15-17 2023

Back to Basics – Seismic Refraction Survey Design

Adam Peake
DMT Geosciences Ltd.

Introduction

The most common use for Seismic Refraction is to establish the approximate location of more competent rock, generally referred to as “Bedrock.” It can also be used to estimate velocity models for Seismic Reflection. The depth of competent rock can vary greatly over the length of a line and to properly design a Seismic Refraction survey it is important to balance the objectives while being cost effective. In particular, to identify targets at shallow depth a tighter spacing of geophones and shot points is required; but how tight is required for a given depth? This presentation will outline a process to effectively design a Seismic Refraction survey. To accomplish this, one must use first principles of Seismic Refraction itself. This involves using “Snell’s Law” and expected layer properties to model refraction distances using layer properties appropriate for the survey in question. DMT has developed a simple executable to help more effectively design surveys based on the expected site conditions. Of additional consideration to minimum requirements is the quality of the result. A simple method known as “plus-minus” can be used to show the most basic display of bedrock but it will lack the ability to deal with unknowns such as velocity inversions and more complicated geology. A robust tomographic inversion can provide a much more detailed understanding of the site but requires differences in survey design.

Seismic Refraction Theory

Seismic Refraction depends on the principles of “Snell’s Law” (Figure 1, left) which is a method to determine the angles of refraction from one medium to another. From that, critically refracted arrival locations back to the surface can be calculated. When a seismic shot is initiated, energy will propagate through the ground in all directions. In the case of two layers where the velocity/density in the second layer is greater than the velocity in the first layer (Figure 1, right), at some angle the energy will critically refract along the interface and then a wave-front will be created by the refracted wave in the first layer. At some distance the refracted wave will arrive before the direct waves. The point at which the energy from the faster layer below overtakes the layer above is referred to as the crossover distance and is related to the depth of the interface.

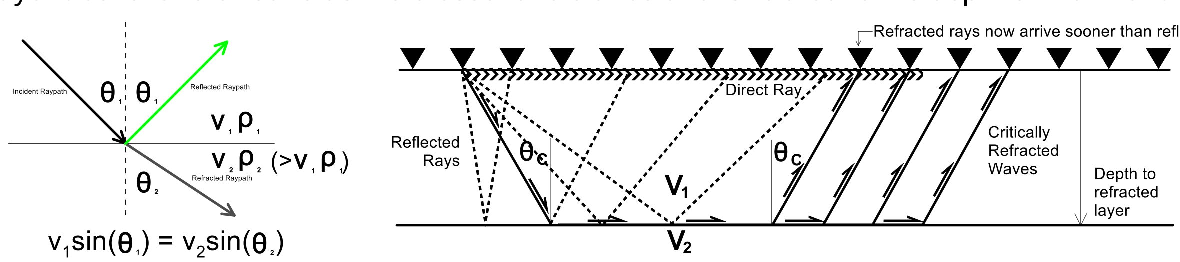

Figure 1: Snell's Law of Refraction (left). Critically Refracted Waves (right).

These arrivals are first to appear on a refraction section and are therefore called “first breaks.” When the first breaks are plotted on distance vs. time, they form “travel time curves.” The shapes of the travel time curves are used to calculate the velocities of layers in the ground. Layer velocities are then used to interpret depth and velocity of overburden and denser materials that might indicate bedrock. Seismic Refraction depends on the assumption of increasing velocity with depth which is generally true, but some layers could be less dense than those above and below leading to a hidden layer problem. This is especially the case for the basic "Plus-Minus Method" of refraction processing. Refraction tomography processing can resolve velocity inversions in some cases due to its advanced nature.

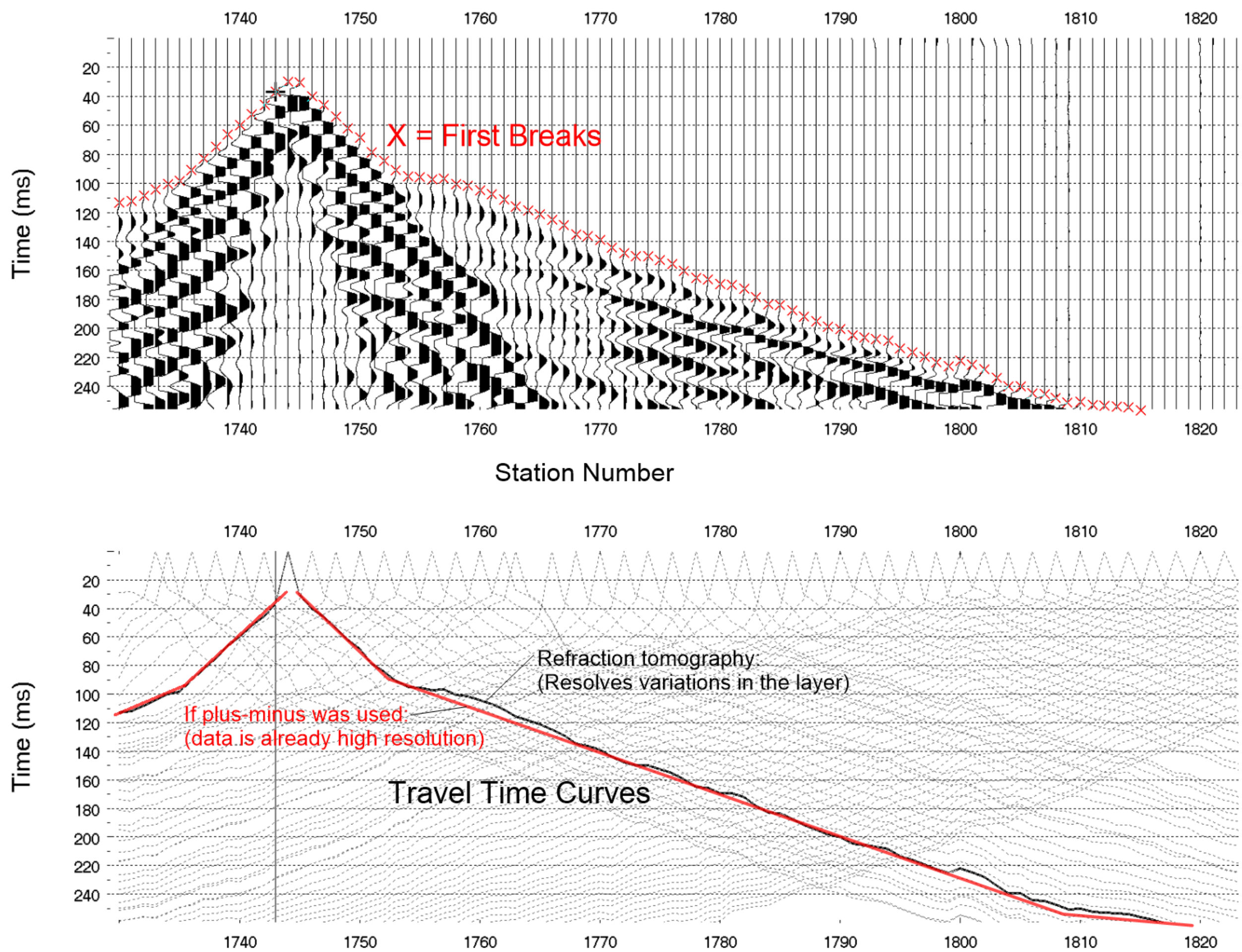

Figure 2: Refraction "First Breaks" (top). Refraction "Travel Time Curves" (Bottom). Note that even when the same resolution data is used for Plus-Minus and Tomography, Plus-Minus is unable to resolve variations within the layers.

Seismic Refraction Survey Design

It is important to design the survey properly in order to capture the first refracted layer (which could be bedrock) and the resolution of the survey required. If geophones are placed too far apart, it may be difficult or impossible to resolve the first refracted arrivals if they are very close to surface. Therefore, an appropriate geophone spacing must be used to satisfy both requirements.

DMT has developed a simple executable (Figure 3) to be used internally for estimation of absolute minimum requirements. It involves entering an expected velocity for the first and second layer and the minimum depth expected for the second layer. These values are estimated using generalized values that are chosen based on lithology information provided by the client or from regional knowledge.

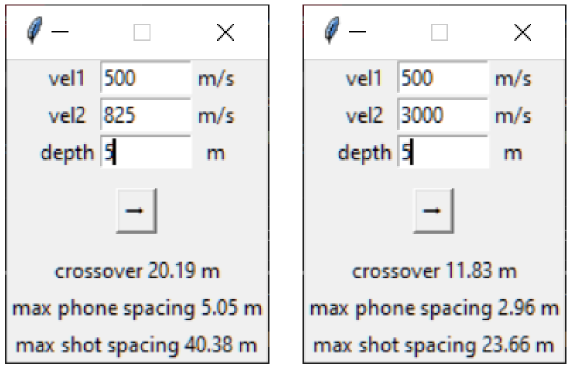

Figure 3: Refraction parameter executable examples.

In the example in Figure 3, the first pane shows that for a Layer 1 velocity of 500 m/s and a Layer 2 velocity of 825 m/s, the maximum geophone spacing in order to resolve the second layer is approximately 5 metres. It also shows that the crossover distance is approximately 20 metres, meaning that in order to show a refracted arrival of the second layer, the line must be at absolute minimum, 20 metres. In order to resolve multiple points of the second layer along the line, a maximum shot spacing of double the crossover distance is required. Smaller shot spacing will increase resolution and data density. These minimums are used as a guide to design for cost and resolution. A larger geophone spacing can be used for a lower cost/lower resolution option (lower reliability), or a smaller geophone spacing can be used for a higher resolution option. The resulting design is generally a balance of the two.

Plus-Minus Method vs. Seismic Tomography

The “Plus-Minus Method” is a basic and low-resolution form of refraction processing to provide an estimation of layering at a site. After first breaks are picked, the inflection points of the picks are selected and a single velocity is assigned for the layers to those respective points. This method is incapable of resolving smaller variations within the layering and has difficulty resolving variations laterally of the layer surface. It is also directly affected by topography changes since it does not take these into account during processing. The result is generally insufficient to resolve changes within a layer (Figure 4).

Seismic Refraction Tomography is an advanced and high-resolution form of refraction processing (Figure 5). DMT collects and processes data in a form so that proper refraction tomographic sections can be created. Note how the bedrock surface is not as greatly affected by surface topography changes. This involves a tighter geophone and shot spacing in order to resolve the changes that tomographic inversion can provide. Figure 4 and Figure 5 illustrate the advantages of acquiring higher resolution refraction data using more shots (generally shooting every second, third, or fourth geophone) and off-end shots. This is due to the processing taking surface topography into account while inverting the data. A sample velocity section produced using the standard plus/minus method for seismic refraction data and sparse shot interval is presented in Figure 4. Only with the higher resolution approach can the drill proven low velocity zone (velocity inversion) on the east end of the survey line be imaged (Figure 5). Plus-minus would not resolve this velocity inversion. This approach also requires great care and understanding of processing techniques as well as the survey design to avoid introducing artifacts to the velocity model. We will explore this in more detail through examples.

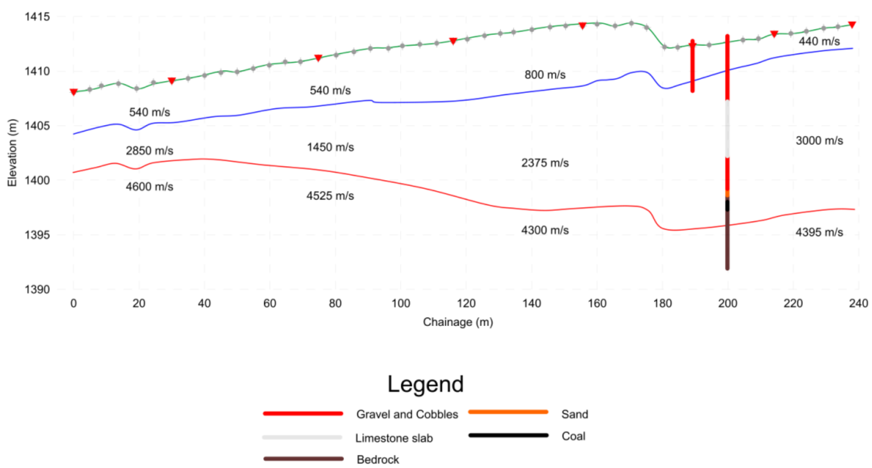

Figure 4: Typical seismic refraction survey section for plus-minus method of processing. Red triangles indicate shot locations. Note how the method is directly affected by topography changes.

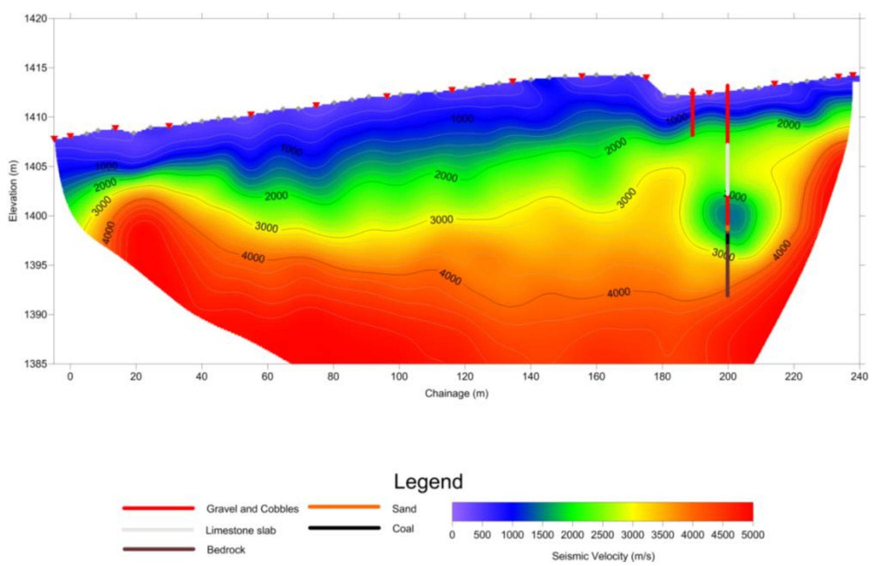

Figure 5: Typical DMT seismic refraction survey section using seismic tomography for processing, showing the same survey line as shown in Figure 4. Red triangles show shot locations. Note that there are many more shots taken than what would be done for the survey in Figure 4. This collection method and processing technique mapped a less dense gravel and cobble layer (velocity inversion) that was beneath a limestone slab and had very good correlation with borehole information. Note how the bedrock surface is not as influenced by topography changes.

Conclusions

Seismic Refraction is a very useful tool for not only near surface bedrock mapping but also for velocity models used in Seismic Reflection processing. Proper survey design using the right spacing for geophones and shots is paramount for producing a quality result. Seismic Refraction Tomography proves itself to be a superior method for determining the location of bedrock and has the potential to map velocity inversions where the older Plus-Minus method does not.