An Overview of the Vertical Seismic Profiling (VSP) Technique

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Abstract

Vertical seismic profiling (VSP) is a seismic technique that measures acoustic waves between a well bore and the surface. It differs from surface seismic by being both higher in resolution and by giving the geoscientist the ability to analyze wavefields in-situ. VSP provides a direct correlation between subsurface stratigraphy and seismic reflections measured at the surface. This provides the seismic data processor with a means by which to calibrate seismic data in the time domain with depth. Additionally, due to its high resolution, VSP can image objects within the vicinity of a well bore that could not otherwise be defined by surface seismic techniques. Even with so many advantages, VSP surveys are far from being a routine geophysical practice. This is due to both the time and huge costs involved with data acquisition.

The focus of this paper is to give an overview of VSP as applied to oil and coal exploration. Classical acquisition practices are discussed from an oil field standpoint. These practices, however, could easily be scaled down and applied to engineering and environmental problems. This paper will tend to shy away from in-depth discussions on VSP data processing, mainly providing information on the value of the technique as well as the field procedures involved.
**Introduction**

Perhaps the most utilized of all geophysical methods is surface recorded seismic reflection. Computer technology has advanced to such a degree that very sophisticated images of the subsurface can be obtained by means of surface seismic reflection techniques. However, even by using advanced seismic processing, surface seismic is limited by the spherical spreading, adsorption and multiples of the down going and received wave forms (IPIMS web site, movie on VSP Survey Fundamentals). Vertical seismic profiling allows a way to correct this surface seismic problem by giving the geophysicist a means of examining the acoustic wave field in situ. Current applications of VSP to surface seismic data include:

- Precise correlation of surface seismic data with depth.

  Vertical Seismic profiling has an advantage over other means of determining reflectivity coefficients (such as by synthetic seismograms derived from sonic logs) because the frequency content is similar to that of surface seismic data (Dobrin and Savit, 1988). Additionally, VSP data usually are not as sensitive to borehole conditions such as washout when compared with other borehole methods (Yilmaz, 1987).

- Separation of Primary Seismic Reflectors from Interbed Multiples

  Zero Offset VSP data gives the seismic interpreter a means of accurately distinguishing multiple reflections from primary reflection events.
• Calibrate Seismic Reflectivity Coefficients Derived from Well Log Data

VSP surveys may be used to correct or validate nearby offset well log derived synthetic seismograms for use in surface seismic time-depth conversion. Supplementing VSP data and synthetic seismograms processed from wireline data acquired in offset wells is a more cost-effective means of surface seismic depth control when compared to using only VSP.

• Provides Seismic Data Processing Parameters

VSP data can provide to the seismic data processor important parameters such as amplitude decay functions and deconvolution operators (Yilmaz, 1987). This is particularly important for more advanced seismic analysis techniques such as Amplitude Variation with Offset (AVO) studies.

Besides being a means of calibrating surface seismic reflection data, Offset VSP three-component measurements of the down going and up going wave fields in a borehole allow for high resolution imaging of the subsurface outside the well bore. This is possible either though ray-trace mapping of reflections from the offset VSP format to a common depth point (CDP) section, or by ray traced Kirchhoff migration (Halliburton Web Site, VSP Services).

VSP images are higher in resolution than surface seismic images because the received wave-fields are direct arrivals from the surface. In a surface seismic survey, the higher frequency data that is recorded in a VSP survey is attenuated by the two way
travel paths of the signal. This allows VSP surveys to image structures too small to be resolved by surface seismic. Additionally, through shear wave analysis, rock property estimation and fracture mapping are possible using VSP. Other applications include, prediction ahead of the bit, bed dip measurements, salt and volcanic proximity surveys, as well as "4D" reservoir characterization.

**Method**

**Check Shots**

The most basic form of a VSP survey, known as a check shot, is used to determine interval velocities to geologic marker horizons. The typical check shot survey involves lowering a geophone/hydophone into a well to a selected position and measuring the time it takes for an acoustic pulse generated at or near the well head to travel to the receiver. Most often an airgun or explosive source is used. Unlike it’s VSP cousin, the receiver locations are often placed hundreds or thousands of feet apart and the recording windows are only long enough to record the directly arriving signals (Dobrin and Savit, 1988).

**Zero-Offset and Offset VSP**

A typical vertical seismic profiling array employs a surface seismic source and a downhole receiver consisting of a specialized geophone or hydrophone. This is illustrated by a typical marine survey in Figure 1 and a typical land based survey in Figure 2. Note that in the marine situation, the drilling or production platform is always present and in the land situation, the hole may be cased and drilling rig moved away. Land based
surveys also allow for the use of more sophisticated sources such as shear wave vibroseis (IPIMS web site, VSP Survey Fundamentals).

Figure 1. Marine VSP Data Acquisition (From IPIMS web site, VSP Survey Fundamentals).
Figure 2. *Land VSP Data Acquisition (From IPIMS web site, VSP Survey Fundamentals)*.

The VSP array can be broken into two categories. Zero offset VSP and offset VSP. Data acquisition is similar in both cases. In the zero offset case, a seismic source such as explosives, vibroseis or other mechanical device (air gun, hammer, etc.) is activated at or near the head of the borehole and a receiver records the signal at fixed depths in the borehole. Several shots are recorded (and stacked) at the same depth interval, the source is moved uphole a fixed amount, and the process is repeated. Unlike check shot data, receiver spacing is typically 50 to 100 feet and record lengths are long enough to include reflections from far below the total depth (TD) of the well (Dobrin and Brown, page 8 of 18)
Savit, 1988). Service companies use the latter to "see" in front of the drilling bit increasing the efficiency of drilling programs. Figure 3 illustrates a Baker Hughes Zero-Offset VSP data set.

Figure 3. Baker Hughes Zero Offset VSP Survey Data (From Baker Hughes web site, Zero-Offset Vertical Seismic Profile).
Once all receiver locations have been recorded, the surface source may be moved a fixed amount away from the borehole and the same receiver locations recorded again. This is known as Offset VSP. Offset VSP allows for the imaging of the subsurface away from the well. The acquisition of Offset VSP data should always include some type of presurvey modeling to determine the proper source location(s) needed to achieve the desired objective(s). Three component (triaxial) geophones are most often used to help separate out, and record the maximum amplitude component of, the many acoustic wave types. It should also be noted that Offset type VSP imaging is possible using a Zero-offset VSP array in a deviated well bore. Figure 4 illustrates a Baker Hughes Offset VSP data set.

Figure 4. Baker Hughes Offset VSP Survey Data (From Baker Hughes web site, Offset Vertical Seismic Profile)
Offset VSP use to image complex structures.

The most classical use of VSP to image complex structures is the salt-proximity survey. First used in the 1940’s, it involves transmission or refraction of energy from a surface source, through the salt, to receiver locations in a borehole (Dobrin and Savit, 1988). More distance between the salt and well results in more low-velocity sediments between the salt and the well, increasing the overall travel time (Figure 5). A newer type of salt-proximity survey uses the reflected energy resulting from the salt face (Figure 6). Either method is most useful when overhanging structures such as salt or volcanics mask the underlying structure on surface seismic data records. Quite often these techniques may be the only reliable method of revealing potential targets and guiding drilling operations in such a geological setting. An example of Baker Hughes salt-proximity survey results can be seen in Figure 7.

Figures 5 and 6. Diagrams of salt proximity surveys. (5) is a transmission or refraction type and (6) is a reflection type (From Dobrin and Savit, 1988).
Figure 7. Baker Hughes salt proximity survey results. This image shows higher resolution VSP data to the right of the well bore and to the left of the salt dome integrated into a surface seismic data set (From Baker Hughes web site, Salt-Proximity Survey).

**Alternative Applications**

Although the above may appear oil field specific, miniaturized versions of the arrays and instrumentation described are used in environmental, engineering, and mining exploration geophysical applications. These techniques almost always translate directly from their larger oil field counterparts. For example, in the case of coal exploration, a
scaled down version of the zero-offset VSP survey has been used with much success.  
Since the receiver is in a borehole below the weathered layer during a VSP survey, the
VSP data has a broader frequency spectrum than conventional seismic data. This
translates to a much more accurate representation of the depth and thickness of the coal
seams, which can later be used to calibrate surface seismic data (Gochioco 1998).

**Evaluation**

More often than not, companies judge the cost of geophysical surveys to out
weigh the gains. The VSP technique is no different. For this reason, it is important for the
designer or sponsor of a VSP survey to be aware of the objectives involved and what type
of VSP survey (if any at all) will satisfy those objectives in a cost-effective manner. There
are many instances when VSP surveys should be seriously considered. These include
when it is necessary to:

- overcome surface seismic no data areas or improve poor data areas such as in
  subsalt imaging.
- resolve subtle structural and stratigraphic features, such as faulting and traps, which are smaller than what can be defined with the bandwidth of surface seismic data.
- establish an absolute depth tie between surface seismic data and subsurface geological markers or predict the distance to reflectors below the current TD of a well
- have as much reservoir information as possible, perhaps for use in lease assessment studies or enhanced oil recovery.
- to tie compressional and shear wave seismic reflectors by measuring in-situ wave propagation and attenuation.
- to accurately identify multiple reflections present in surface seismic data
- to calibrate sonic log derived synthetic seismograms to a check shot type response and bandwidths or convert well log data into the time domain
Given all the situations above that list when VSP should be considered, it is amazing that it is not a routine geophysical practice. The reason for this is the tremendous time and cost involved with the method. Consider the first ever combined 3D surface seismic and 3D VSP survey conducted onshore in Europe by the French company CGG. Its purpose was to better illuminate the seismic response both below and along the flanks of a salt structure. The survey required almost 3,000 shots of dynamite and over two weeks to complete! (CGG Web Site, First Combined 3D surface seismic and 3D VSP) Given the current situation with the pricing of oil, many companies could not justify the cost of such an undertaking without remarkable rewards.

So what is it that makes VSP data so slow to acquire? Besides the time involved in wiring many explosive shot points, the triaxial geophone(s) must be positioned and locked to the borehole wall at each receiver location. Unlike surface seismic, the operator can’t throw out many receivers and simple "roll-along". In fact, it is not uncommon to use only one receiver to record an entire VSP survey due to the trouble involved in positioning and locking many triaxial receivers downhole at one time. This leaves much room for the improvement of VSP field technique.

Discussion

It should be clear that the one major problem with the VSP method is the inefficiency involved with data collection. The main cause of this inefficacy is the need for the downhole receiver to be coupled to the borehole wall at each receiver location.
Potential ways around this problem include the use of Reverse VSP (RVSP), hydrophones, and drill noise as the source.

RVSP is a logical alternative to VSP. Reverse VSP is performed exactly how the name suggests. The receivers are planted on the surface and the source triggered downhole. Such an approach takes advantage of the easy placement of many triaxial geophones on the surface and a source that doesn’t have to be coupled downhole. Comparing the two techniques, it has been found that RVSP stacked sections produce higher frequency images at shallower depths than do VSP stacked sections. The lower frequency VSP stacked section, however, produced an interpretable image at much greater depths (Zimmerman et al, 1993). The main cause for this is that the strength of the downhole source in the RVSP survey was weaker than the surface source used in the VSP survey. Secondly, tube waves (wave multiples traveling up and down the borehole) amplified by the source being down hole where difficult to strip from the RVSP data set (Zimmerman et al, 1993). A stronger non-destructive downhole source (such as some form of airgun) and a better means of removing the intensified tube wave multiples resulting from such a source would literally give the more cumbersome VSP method a run for its money.

Another logical approach to expedite VSP data acquisition is to run VSP surveys using hydrophones instead of geophones. Hydrophone strings have the distinct advantage of not having to be coupled to the borehole. They are a proven technology and many sensors (hence many receiver locations) can be hung down the hole at one time. When comparing Geophone VSP data to Hydrophone VSP data the problems are similar to RVSP. The hydophone data, although higher frequency, does not image as deep as the
conventional VSP data. This can once again be attributed to tube waves. Hydrophones are much more sensitive to the tube waves produced in a borehole than the coupled geophones, hence making it difficult to interpret deeper events (Zimmerman et al, 1993). Another misfortune with hydrophones is that they are simple pressure transducers. They are incapable of detecting the polarity and amplitude of a waveform in three dimensions. This means that three-component data processing techniques used to discern the different wave arrivals (such as P, SV, SH etc.) can not be applied to hydrophone data.

Currently one of the most exciting technologies in the geophysical community is drill noise RVSP. Drill noise RVSP involves placing receivers on the surface and using drill noise as the source. A drill noise VSP study was conducted to a depth of 4000 m in Germany. The authors reported a signal bandwidth comparable to surface seismic data but inferior to conventional VSP data (Haldorson et al, 1995). Results aside, combining acoustic logging while drilling, drillnoise RVSP, and almost real time processing would be very a powerful tool. Identifying and positioning marker beds, determining their interval velocities, and imaging both around and ahead of the bit would be possible without the driller even pulling out of the hole. The benefits of such data combined with the relative low cost of acquisition may be what are required to indeed make the Vertical Seismic Profiling technique routine.
Conclusions and Recommendations

Despite the cost involved with vertical seismic profiling, it will always remain an indispensable tool. The information that VSP is capable of providing can currently be equaled by no other geophysical survey method. With the advent of new measurement while drilling techniques such as drill noise reverse VSP combined with more advanced instrumentation and processing, it will not be long before VSP surveys will be as common as surface seismic and wireline data acquisition. Until that day, however, it would be wise to clearly define exploration objectives before considering VSP as a cost-effective geophysical solution.
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