3D S-wave statics from direct VSP arrivals
Michael J. O’Brien, Allied Geophysics, and Paritosh Singh, Colorado School of Mines

Summary

We observe that direct S-wave arrivals in 3D VSP data contain the information needed to find the S-wave statics solution for 3D surface seismic. This solution is independent of P-wave data. We show S-wave statics computed from VSP data can improve the alignment of shear reflections seen on 3D surface seismic shot records, making these events easier to analyze and process with common “flat-earth” assumptions.

Introduction

The derivation of source statics from VSP first breaks is not new. It has commonly been done for walkaway VSPs (Kragh et al., 1991; Liu and Owusu, 2005; Libin et al., 2009), and also for 3D VSPs (Paulsson et al., 2004). In these prior works, the statics found from VSP data were applied only to VSP data. It is also well known that VSPs and surface seismic have many complementary attributes, including statics (Constance et al., 1999). Kragh et al. (1991) showed that, by using downhole sources in a so-called hole-to-surface geometry, a receiver statics solution is also available. An example of applying P-wave statics derived from VSP data to surface shot records was shown by Tabakov and Baranov (2007). Here we propose to combine the ideas of Tabakov and Baranov with those of Kragh et al., to find a complete S-wave statics solution for 3D surface seismic data.

Method

Since we have limited field data, the examples shown in this study come from a 3D, anisotropic, elastic model; however, the field data we do have has the same character that we exploit with model data examples (Figure 1). In order to get a complete statics solution, two VSPs are needed. First we record data from surface sources into downhole receivers, and then from downhole sources into surface receivers (Figure 2). The 3D source and receiver line geometry we modeled is shown in Figure 3. We acquired 16 source lines and 16 orthogonal receiver lines. Both source and receiver lines are separated by 200 m; stations along the lines are separated by 33 m. The underlying map in Figure 3 is a color contour map of one-way $S_2$-wave (slow shear wave) time through the near surface of the model. The differential static across the map area is 0.150 sec.

In addition to building a near-surface problem into the model, HTI anisotropy has also been added. The Thomsen parameter gamma and the azimuth of HTI isotropy planes vary in space (O’Brien, 2010). Our current work emphasizes S-wave statics only, though much more could be learned by analyzing the many other facets of the 3D-9C data.

Our method is straightforward: fit a least-squares hyperboloid to the S-wave first-break picks and apply the time differences between picks and the hyperboloid as a statics solution for surface seismic data. If necessary, a more sophisticated fit
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Could be used. The closer the fitting method is to the real problem, the more accurate the surface fit will be. We picked first break on raw data and no effort was made to align source and receiver components to the principal anisotropy axes of the model.

The equation for a hyperboloid can be expressed as $t^2 = S_x x^2 + S_y y^2 + S_z z^2$, where $(S_x, S_y, S_z)$ is a slowness vector, $(x, y, z)$ are spatial coordinates and $t^2$ is the hyperbolic surface. Since each first-break pick is characterized by $(t, x, y, z)$, minimizing the squared error between squared pick times and the $t^2$ surface produces coefficients of squared slowness in three directions (Figure 4). This means that aside from a statics solution, information about the maximum horizontal stress direction in the HTI medium is also available.

Discussion

Figure 5 shows an example of how the least-squares hyperboloid (blue) fits the first-break picks (red) for source lines 3 and 9. The difference between the two surfaces can be called the relative static for the surface position of the data (either a source or receiver station). Using surface-to-hole and hole-to-surface VSP datasets, source statics and receiver statics can be computed independently or simultaneously. Maps of independently computed source and receiver statics are shown in Figures 6a and 6b. Similarities in the shapes of the anomalies are a good indication that the solutions are consistent and correct. It is also possible to use source and receiver statics together to find a unified, surface-consistent solution. To compute the surface-consistent solution, our method of least-squares surface fitting requires a single location for both source and receiver. This might be achieved...
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Figure 6. Statics solutions can be computed from source data alone (A), receiver data alone (B) or from source and receiver data simultaneously (C). In these images, the least-squares fit of all three data combinations results in statics maps with the same overall structural features. The structural similarity of maps A, B, and C with times computed in the model (Figure 3) give us confidence that the data-derived solutions are of high quality.

Figure 7. S-wave 3D surface seismic data without statics applied (top), and with VSP derived S-wave statics applied (bottom). After statics are applied, the shallowest high amplitude event has the continuity and hyperbolic shape that will facilitate analysis and processing with common “flat-earth” methods often used.

in cased wells using non destructive downhole sources. A statics map that represents such a solution is shown in Figure 6c.

An example of applying the statics from Figure 6c to 3D surface seismic data is shown in Figure 7. The upper half of Figure 7 shows common-shot data without statics applied, and the lower half shows the same traces after VSP-derived S-wave statics were applied. The statics-corrected data in the lower half of Figure 7 shows a marked increase in continuity of S-wave reflections.

Using the model for QC

Since these data were calculated in a model we can QC our data-derived statics by comparing them to vertical times--computed directly from the model. Figure 8 shows a comparison between data-derived statics (green) and vertical S-wave time from the model to a depth of 250 m (magenta). Results for far-offset and near-offset source lines (Lines 3 and 9 respectfully) are shown in this figure. We observe that at the nearest offsets of Line 9, the data-derived statics are a good match to statics taken directly from the model. But we also note that as offset increases toward the ends of Line 9, the data-derived static increases relative to those from the model. We also note that on Line 3, which is ~1100 m away from the VSP well, the data-derived solution has longer statics delays for the entire source line. We call the extra time seen in the data-derived statics a time delay relative to vertical time from the model.
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To show the cause of this systematic increase in time delay with offset, we extracted a 2D slice, diagonally through the model. That slice starts at the northwest corner of the survey, passes through the VSP well, and ends near the southeast corner of the survey. From the locations where the 2D slice intersects 3D source lines, we traced 2D rays to a downhole receiver (Figure 9). We then accumulated time along ray paths to a depth of 250 m and converted those to time delays relative to vertical time. For the 15 source line intersections we analyzed, we plot the ray-traced time delay and the data-derived time delay in the bottom part of Figure 9. While imperfect, there is a general agreement between the two datasets. This suggests that as offsets increase, the assumption that static time delays follow vertical paths is less accurate.

Conclusions

We have extended the ideas of others to develop an S-wave statics solution that is independent of P-wave data. The method uses direct-arrival S-waves from surface-to-hole and hole-to-surface VSP acquisition. We have shown that statics computed in this way can increase the continuity of S-wave reflections in 3D surface shot records, making them easier to analyze and process with common tools. Our solution is simplistic in that it uses a least-squares hyperbolic fit to a first-break time surface. This type of fit assumes horizontal layering and a constant, but directionally variable, velocity field. A more general solution is available if the time surface is created by forward modeling through a heterogeneous model. Finally, because we can compare our solution with vertical times computed in the known model, we are able to show that vertical path assumption of statics corrections becomes less accurate with increasing offset.

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References


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