Feasibility analysis of drill bit tracking using seismic while drilling technique

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SUMMARY

Check-shot survey measures the first arrival time with a known depth receiver in borehole to assess formation velocity. This information can be used in correlation with sonic log and surface seismic products for adjustment of interpretation. Check-shot survey can also be implemented with seismic-while-drilling using drill bit noise as the source. This differs from usual check-shot survey as source is in the borehole. It provides a real time, cost saving, and safe measurement.

Check-shot survey needs a known receiver depth, thus velocity can be obtained by fixed wave travel path and the measured first arrival time. However, in seismic-while-drilling (SWD), drill bit position can vary a lot from vertical drilling to deviated drilling. To address this issue, we present a method that finds the location of the source and estimates the velocity of the formation at the same time. Using a synthetic model, with medium receiver offsets, this method shows good estimation of the drill bit depth location and formation velocity in a layered Earth model.

Key words: check-shot, seismic-while-drilling, slowness

INTRODUCTION

A drill hole direction variation is well understood. If there is no good monitor and control in place, drill bit position variation in directional drilling is usually larger than vertical drilling. To perform check-shot survey, borehole deviation survey is required. This means to measure the borehole departure from the well plan. In a drilling of straight hole, the surveys are taken periodically with a mechanical drift recorder attached to a wire to measure the angle of the hole. For a directional borehole, MWD (measurement while drilling) tool uses electronic accelerometers and gyroscopes, to continually measure the azimuth. This tool is normally placed in bottom hole assembly (BHA), hence the sensors have higher risks of failure in drilling environments, which might lead to higher MWD costs.

In seismic exploration, a check-shot survey uses borehole seismic data to measure the seismic travel time from surface to a known depth, where p-wave direct arrival wave is commonly used. Check-shot survey needs known receiver depth, thus velocity can be obtained by fixing wave travel path and measuring the first arrival time. Conventionally, check-shot surveys are usually conducted with surface source and downhole recording. However, as suggested by Poletto (2004), Seismic-While-Drilling (SWD) imaging technique can be also used for a check-shot survey. SWD is an emerging imaging technique in the petroleum industry, which uses drill bit vibration as seismic source and records the seismic signals with surface geophones near and around the drill rig, can be also used for a check-shot survey. SWD check-shot survey is not only able to obtain formation velocity information, but also estimate drill bit position, which helps well navigation and casing (Underhill & Esmersoy, 2001). In addition, this method is more cost effective and safe for drilling optimisation than the standard surface check-shot.

In a constant effective velocity medium, Poletto proposes a check-shot implementation by observing the first arrival time at zero offset, then finds angle α linking t_0 and t,

$$t_0 = t\cos\alpha$$
$$\alpha = \arctan\frac{S}{d},$$

as illustrated in Figure 1. In this equation, S and d are the receiver offset and bit depth, respectively. For layered media, this equation is only approximation for small offset and large depths (Poletto, 2004). The possible issue with this method is that the zero offset signals in SWD are vastly affected by drill rig noises.

To study the potentials of conducting check-shot survey using far offset receivers, we developed a method that uses horizontal slowness (also called the ray parameter) measured at the surface to estimate the drill bit position and formation velocity. This method is based on the fact that the slowness vector is perpendicular to the wave front, thus points to the direction of the drill bit. However, slowness vector is not directly observable at surface, but its horizontal component can be directly measured. We can formulate equations based on the Pythagorean theorem to derive the drill bit depth and the velocity. This method provides a good approximation in layered Earth models, even including gentle dipping layers and simple fault zones. In application of this check-shot method in SWD, its output is of value in verifying drill bit position for SWD imaging, as well as deriving velocity information for correlation with sonic log or surface seismic data. This velocity can also be potentially used for migration.

METHOD AND RESULTS

Slowness vector is commonly analysed in seismic processing, its direction is perpendicular to the wave front propagation in isotropic medium. It can be decomposed into horizontal phase slowness and vertical phase slowness in orthogonal coordinate, expressed as $p = (dt/dx, dt/dz)$. Horizontal phase velocity is constant with depth, and also it can be directly observable at the surface (Claerbout, 2010) . The relations among these quantities are illustrated in **Figure 1**,

$$p = 1/v\,,\ p_x = dt/dx$$

$$p_x = p\cos\theta\,, \tag{1}$$

where θ is the angle between p_x and p.

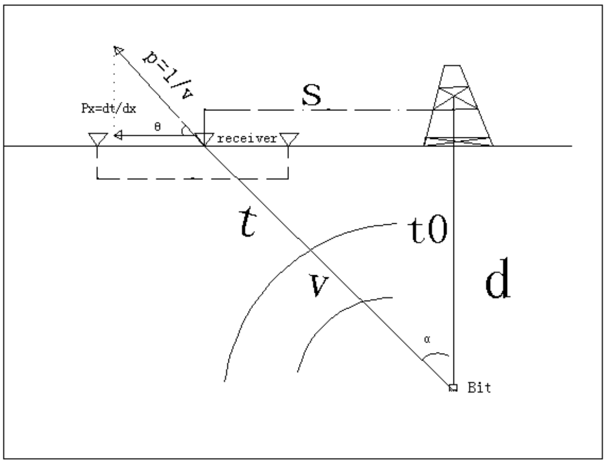


Figure 1 – method to use horizontal phase velocity to estimate drill bit depth and formation velocity

Figure 1 shows the geometry of drill bit and its receiver station. Based on the Pythagorean theorem, geometrically, triangle formed by bit, receiver, drill rig and the triangle formed by the slowness and its horizontal component have a common angle, thus we can formulate two following equations.

$$t = \frac{\sqrt{s^2 + d^2}}{v} \tag{2}$$

$$p_x \times v = \frac{s}{\sqrt{s^2 + d^2}}\,, \tag{3}$$

Where t is the first arrival time at the receiver, s is the horizontal distance between the receiver and the drill bit coordinate. In vertical drilling, this represents distance between receiver and drill rig, but, in a deviated bore hole, drill bit horizontal coordinate needs to be estimated, as we discuss later in this paper. v is the velocity of the formation, in a layered Earth, this velocity is the normal move out velocity, which is approximation of RMS velocity, d is the drill bit true depth, p_x is horizontal slowness

$$p_x = dt/dx\,. \tag{4}$$

dx can be easily defined by the receiver intervals. dt is the change of the first arrival time with the change of the receiver. The accuracy of its estimation directly affects the final outcome, so care should be taken in its computation. One conventional method to find the time shift is cross correlation. However, this method might be limited by the sampling rate; the time shift between two traces is always multiple of sampling interval. When picked two receivers are not separated at sufficient distance, cross correlation will not generate accurate time shift. To avoid this problem, we find the time shift in the Fourier domain. The time shift in the time domain is corresponds to the frequency dependent phase change in the frequency domain:

$$f(t - dt) \Leftrightarrow F(\omega)e^{-j\omega dt}\,, \tag{5}$$

where dt is the time shift.

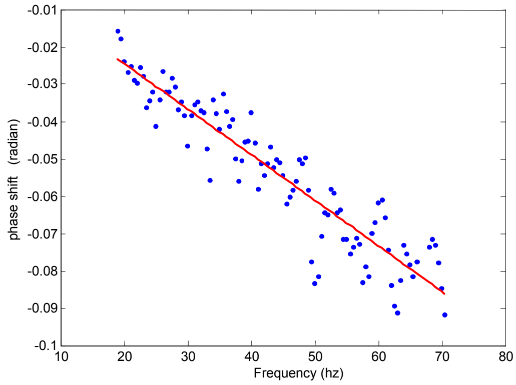


Figure 2 - phase shift vs frequency plot (sp2 first two traces in velocity model Figure 3)

Figure 2 shows this phase change for the first two neighbouring traces computed from velocity model in **Figure 3**. The time shift dt is calculated as the slope of phase difference versus frequency. A linear least square fit is used to compute the slope, as indicated by the red line in the figure:

$$dt = \frac{\sum_{k=1}^{n} f(k)dp(k)}{\sum_{k=1}^{n} f(k)^2}\,, \quad k = 1, 2 \ldots n \tag{6}$$

Unlike for active surface seismic surveys, where the first arrival time is relatively easy to be observed, in SWD this could be a real issue, since the first break time is normally picked after the pre-processing of SWD data, which include cross correlation of pilot signal with seismic traces. The first arrival time obtained from the cross correlation is the time difference between the travel times in the pilot signal and the corresponding times in the processed trace:

$$t = t_c + t_p\,,\ t_p = Z/V_{ds}\,, \tag{7}$$

where t_c is the picked time after the cross correlation, t is real first arrival time, and t_p is pilot sensor first arrival time, Z is drill string length, V_{ds} is average drill string velocity (Miranda, 1996).

Time delay to pilot sensor t_p from the drill bit can be calculated from first long multiples in the drill string, or alternatively, if we know the average drill string velocity, we can derive the t_p by equation (7). This common delay is added to the first arrival time computed from cross correlated geophone and pilot traces.

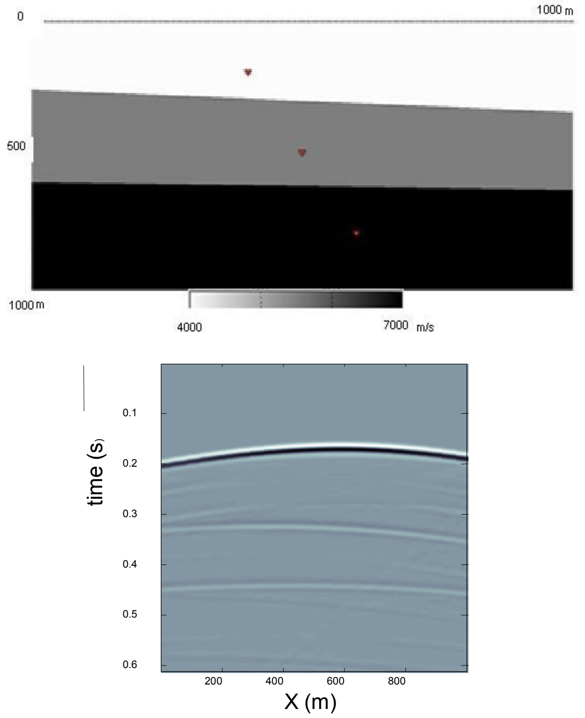


Figure 3 – Top: layered Earth velocity model, Bottom: sp3 seismic section

As discussed above, when the trace time shift and first arrival time are determined, we can use equations (2) and (3) to find the unknown v (velocity) and d (drill bit depth):

$$d = \sqrt{\frac{t}{p} \times s - s^2} \quad \textbf{(8)}$$

$$v = \sqrt{\frac{s}{t \times p}} \quad \textbf{(9)}$$

To test the above equations, we first use velocity model in **Figure 3**. The three triangles represent source points buried in each layer. From top to lower layer, source point depths are sp1 (200 m), sp2 (500 m), sp3 (800 m). We model 201 receivers that are located on the surface with 5 m spacing. Bottom plot of the figure is a sp3 seismic seiction. To use equations (8) and (9), we need to find the horizontal slowness, the first arrival time, and the offset of receiver and drill bit as discussed above. **Figure 4** and **Figure 5** illustrate the resulting drill bit depth and velocity at each receiver point for the three source points. The three source point horizontal coordinates are 400 m 500 m and 600 m, respectively, and are marked by circles in **Figure 4**.

Depth estimations are shown in **Figure 4**, for the top constant velocity layer, obtained depth (200 m) exactly matches the true depth, and for the 2nd and 3rd layers, results are slightly above the true values of 500 m and 800 m, respectively. This overestimation is due to the velocity increase in the layered model, where the actual ray paths are not straight. However for deeper shot points, these results are acceptable as a good approximation. In a future research, correction for the depth bias could be considered.

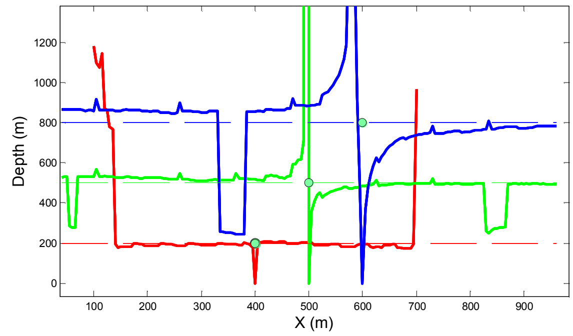


Figure 4 - derived sp depth, red line is sp1 (true depth 200 m-red dashed line), green line is sp2 (true depth is 500 m-green dashed line), blue line is sp3 (true depth is 800 m-blue dashed line), circles are drill bit coordinates.

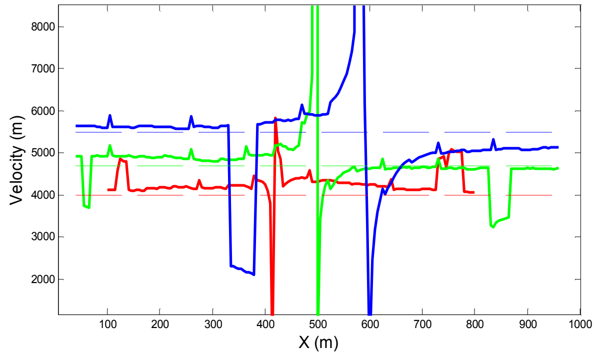
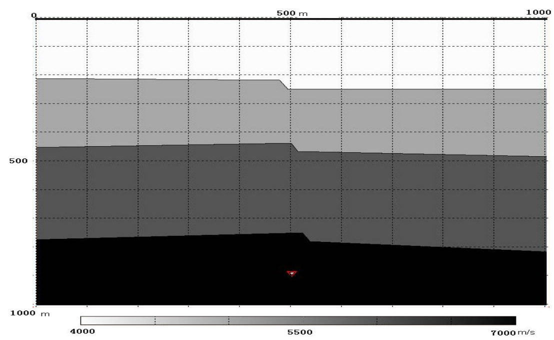


Figure 5 - derived velocity, thick red line is sp1 (top layer velocity is 4000 m/s), thick green line is sp2 (middle layer velocity is 5500 m/s), thick blue line is sp3 (bottom layer velocity is 7000 m/s), narrow dashed lines are RMS velocity obtained from each layer

Derived velocity estimations are shown in **Figure 5**, around 4000 m/s, 4700 m/s and 5500 m/s, respectively. These velocities are the normal move out velocities, which match the RMS values (dashed line). Derived depth and velocity from sp1 (red line) are plotted range from 100 to 800, the results are clipping at outside of the range. This shows that this method works at a medium offset.

For SWD, this method allows for a continuous output of velocity information, which can be used to check with the logging data, and might be applied as a velocity model for seismic migrations.



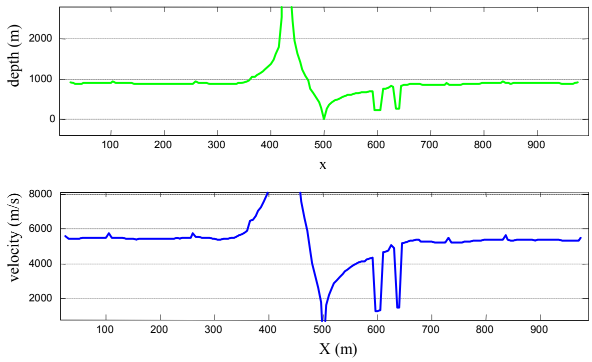


Figure 6 - 4 layers Earth velocity model - shot point depth (900 m) and velocity (from top to bottom, 4000 m/s, 5000 m/s, 6000 m/s, 7000 m/s)

The second model to test the method is shown in **Figure 6** – a four-layer Earth model with a simulated fracture fault zone. A source point is located in the bottom layer under the simulated fracture zone. There are still good estimations of the depth and velocity, where smooth and accurate results are achieved.

Note that the presented method produces spikes and drop offs in the depth and velocity plots for near offsets. This limitation of the method is due to the ray path being almost vertical at near offsets, so the ray and the vertical line passing through the source are not intersected.

The randomly distributed errors in the estimated depths and velocities are due to the errors in the picked trave time.

This drill bit check-shot method is based on known drill bit horizontal coordinate. In a vertical drilling, drill rig is considered as bit horizontal position, without using this method in vertical drilling, approximated drill bit depth can be found simply by sum of drill string length, so in this case, the most important check-shot output is velocity information in relate to receivers. Under other circumstances, in a deviated borehole, to still apply this method, drill bit horizontal coordinates need to be estimated.

One method to find drill bit horizontal coordinates is to compute ray parameter value for each surface receiver. Based on the horizontal slowness theory, when ray path is vertical, horizontal slowness $p_x = 0$ (Xiucheng Wei & David Booth, 2006), because ray parameter is horizontal component of slowness vector, at near offset, slowness and its horizontal component is almost orthogonal, then a minimum value would be obtained, thus we can estimate the drill bit horizontal position by looking for this minimum horizontal slowness.

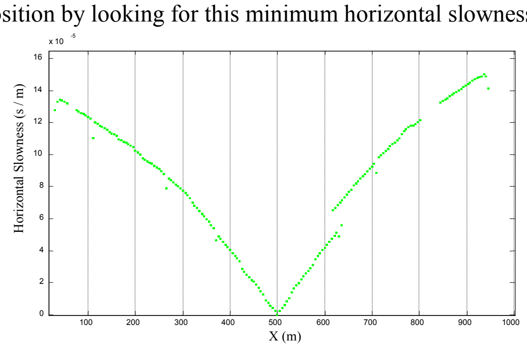


Figure 7 – absolute value of the horizontal slowness based on sp 2 in model 3

Figure 7 is an example of sp2 horizontal slowness at each receiver station derived from **Figure 3** model. The calculated minimum slowness point is at 500 m, which is the correct true drill bit horizontal coordinates.

CONCLUSIONS

We present a method for check-shot survey with synthetic pre-processed drill bit seismic field, which uses the slowness vector direction and its horizontal component to find the drill bit location and the normal move out velocity at a given receiver. This velocity information output is good representation of RMS velocity. Therefore, with a drill bit check-shot survey, continuous velocity information output is useful in correlating sonic logs, tie the surface seismic data, and also for in-front-bit imaging.

This method is only reliable when the time shifts between traces and the first arrival times are properly obtained. To achieve this for SWD, a good quality pre-processed data is important. This method does not apply only to a drill bit, but it can be used for any sub-surface seismic source, where there is a need for source position and formation velocity survey.

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