Uncertainty Analysis of Hydraulic Fracture Parameters Measured by Tiltmeter Mapping

Pinnacle

GET RESULTS

- Identify Source of Uncertainty
- Get Measurement Precision
- Obtain Boundaries for Frac Dimensions

As the old saying goes, everything in life is uncertain except death and taxes. This is true of all measurements including weight, volume, diameter, time, distance *and* tiltmapping.

Pinnacle has expanded the operating range of surface tiltmeters from less than 5000' to more than 15,000'.

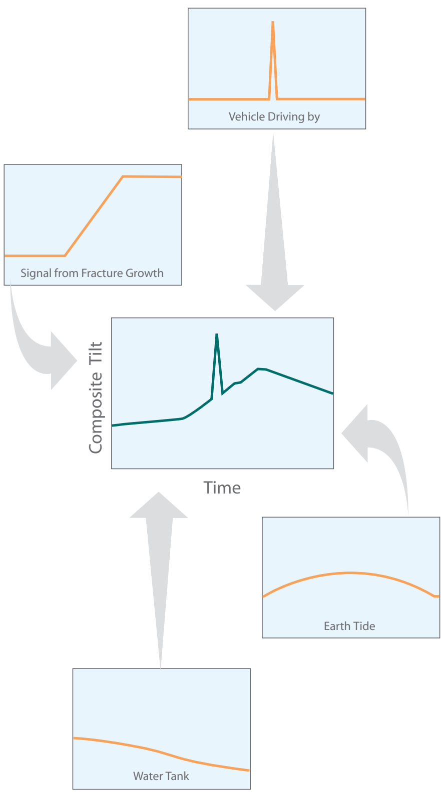

Figure 1. A measured tilt signal is the sum of the signals from the fracture and those from other events.

Major sources of error

Analysis of hydraulic fracture characteristics from tiltmeter data is subject to two major sources of error: measurement error and model error.

Measurement error includes all of the factors that could contribute to errors in the measurement of tilt induced by the fracture treatment. Sources of measurement error include tool calibration errors, tool position and tool orientation errors. However, by far the largest contributor to measurement error is the unwanted measurement of surface deformation due to sources other than the hydraulic fracture treatment. Some of these sources include thermal motions, nearby water tanks that change level during the treatment, vehicles driving past the instruments and earth tides.

Modeling error includes all of the factors and assumptions that can make the calculated theoretical tilt at each tiltmeter site different from the actual tilt. Sources of modeling error include heterogeneity in the rock between the fracture and the tools, a non-planar free surface and complexity in the fracture shape. The first two sources of error could be significant in very extreme cases, but the third is likely the largest source of error for nearly all treatments where modeling error is larger than measurement error. Generally, this is the case during mapping of treatments using downhole tiltmeters in an offset or treatment well.

Which source is most important?

Surface Tiltmapping

As a rule, surface tiltmeters are located far away (meaning many times the longest fracture dimension) from the fracture. Thanks to this distance, the errors introduced by incomplete modeling of the details of the fracture are insignificant. From far away, the fracture appears as an oriented dipole; the tilt field is highly sensitive to the fracture azimuth, dip, volume, and depth, but not to individual fracture dimensions. Since the individual dimensions cannot be resolved anyway, the details of how those dimensions are modeled make little difference in the analysis. Also, since the tools are far away from the fracture and generally close to the earth surface, the measured signals are small and disturbances from surface sources (water tanks, trains, thermal motions, etc) and earth tides may be as large or even larger than the signal from the fracture treatment. For these treatments, the effects of measurement error are much more important than the effects of modeling error. Considering the sources of measurement error, even large errors are normally localized to very few sites so the contour's fit across a large array is largely unaffected.

Downhole Tiltmapping

When mapping fractures using downhole tiltmeters in an offset well or treatment well, the instruments are much closer to the fracture. For these situations, modeling errors can be very significant. Furthermore, tools close to the fracture almost always have very large signal to noise ratios, often of order 100 or more. With large S/N ratios, the measurement error is negligible. The uncertainty no longer centers around the question of how accurately the deformation has been measured, but instead on what the measurement implies about the fracture growth nearby.

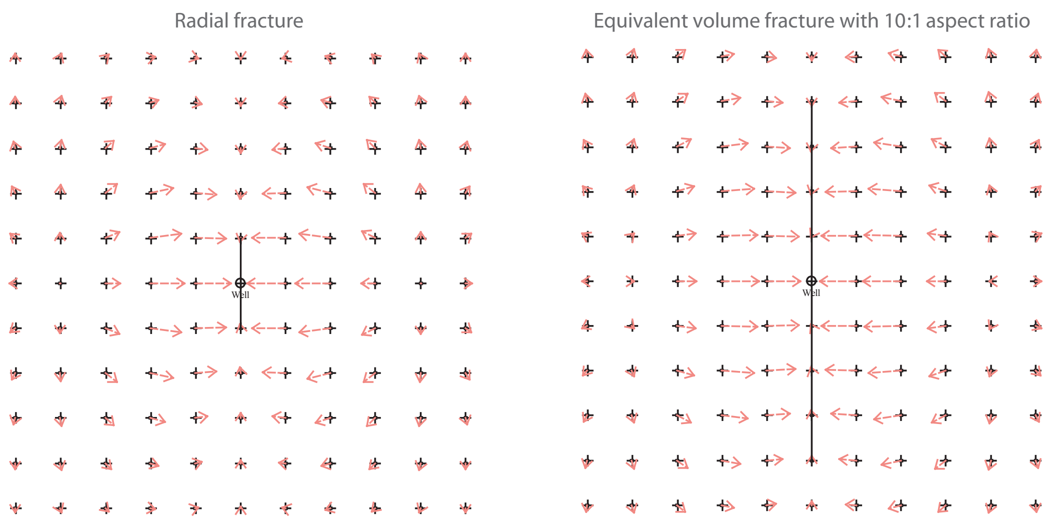

Figure 2. Surface tilt patterns around 2 different vertical fractures. Both fractures have the same volume, but different dimensions. The similarity between the patterns shows that surface tilt mapping is generally insensitive to individual fracture dimensions unless the fracture depth becomes comparable to the fracture dimensions.

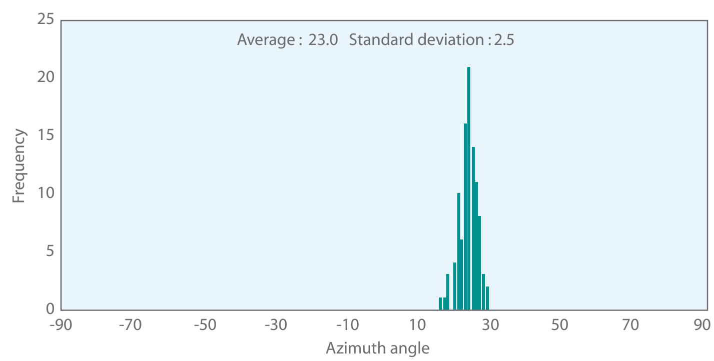

Figure 3. Output of a Monte Carlo analysis showing the azimuth uncertainty from actual surface tiltmeter measurements at 4500'.

Quantifying Measurement Uncertainty—Monte Carlo Analysis

The Monte Carlo method of uncertainty analysis is designed to answer the question "Given uncertain measurements, what set of fracture solutions covers the range of possible earth deformation patterns?" The question is answered by assuming the measured tilt is incorrect by some amount, changing each tilt measurement in a random direction then finding a new solution to fit the revised measurement.

The following procedure calculates the uncertainty in the fracture parameters:

1 The noise level in the data is evaluated by measuring how much signal would be extracted during a time when no signal should be present. Most commonly, data is used from a period 24 hours before the actual fracture treatment to determine average noise levels.

2 The measured tilt at each site is modified by a noise vector. The noise vectors have random orientations and magnitudes that follow a Gaussian distribution with the same average as the measured value from Step 1.

3 An inversion routine finds the fracture parameters that best fit the modified tilt data. The frac parameters produced by the analysis are stored in a database.

4 Steps 2 and 3 are repeated 100 times with a different set of noise vectors each time.

5 The uncertainty is reported as the standard deviation of the fracture parameters in the database.

This method accounts for randomly distributed errors in tool calibration, tool position, tool orientation and perturbations unrelated to the fracture treatment. It does not account for systematic errors in tool calibration, tool position, and tool orientation, but these errors are easily made negligible by careful field operations and a program of checking data. For instance, tool calibrations can be verified in the field to a reasonable degree of accuracy by mapping the earth tides, which have a known magnitude.

Quantifying Modeling Uncertainty—Error Surface Analysis

The Monte Carlo Analysis shows the range of possible fracture solutions when measurement error dominates, but fails to show the proper results when measurement error is small compared to modeling error. Since the inversion routine in step 3 will always find the best fit fracture to the measured data, if there is very little uncertainty in the measured data the routine will always come up with same best fit solution and hence a low uncertainty, even if the modeled fracture doesn't fit the measured data very well. For these situations, another method of evaluating the uncertainty is required. The error surface analysis is designed to answer the question "Given a set of high quality tilt measurements, what range of fracture parameters might reasonably produce those measurements?"

Mathematical models of hydraulic fractures are, at best, incomplete representations of the real thing. Most fractures are modeled as rectangular dislocations, with constant width between the faces. For treatments where tools are extremely close to the fracture, a more sophisticated and much more complicated model with elliptical cross sections is used. Real fractures, however, may have offshoots, varying widths across their height and length, different heights across their length, etc. In a few cases, there can also be a significant contribution to

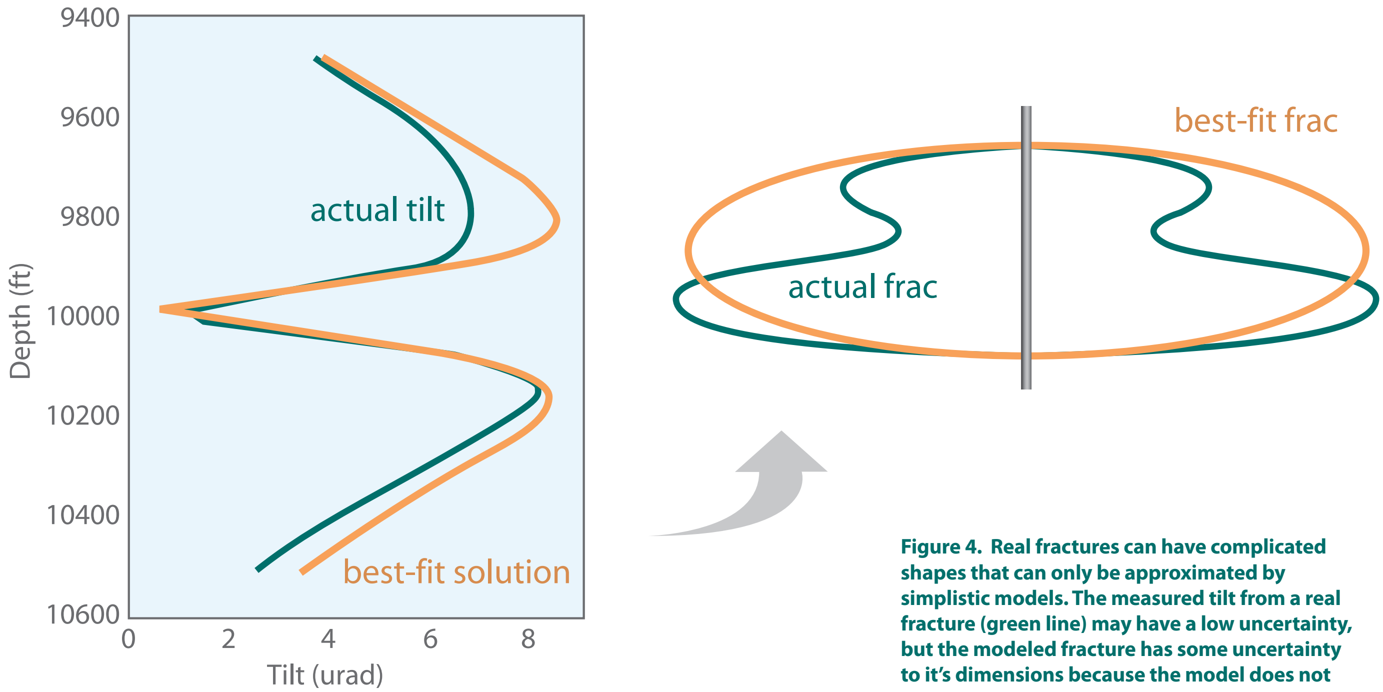

Figure 4. Real fractures can have complicated shapes that can only be approximated by simplistic models. The measured tilt from a real fracture (green line) may have a low uncertainty, but the modeled fracture has some uncertainty to it's dimensions because the model does not precisely fit the measurements.

the deformation from the increased pore pressure around a fracture.

The error surface analysis determines the sensitivity of the theoretical tilt to changes in the fracture parameters. If the theoretical tilt changes quickly with small changes in a fracture parameter and the measurements themselves have very low uncertainty, the result is robust and the fracture parameter is well known. There are cases, however, where even though the measurements are taken with a high degree of certainty, significant changes to the model result in only small changes to the theoretical tilt, so the uncertainty can still be high.

The process of running the error surface is to force the model to step through a range of fracture parameters and plot the fit error (that is, a parameter that measures how well the theoretical tilt matches the measured tilt) against the fracture parameters. The process is similar to a brute force optimization. In some cases, as shown in Figure 5, the method shows that the fracture length and height are both well constrained by the tilt data. Even a small change in the modeled fracture dimensions results in a poor fit with the measured data.

Sometimes, though, the results show that 2 (or more) fracture parameters can be traded off against each other with little change in the theoretical tilt pattern. In the example on the next page, there is a minimum error with a 300 ft long, 275 ft tall fracture, but the error surface also shows that there is a minimum half-length of about 250 ft, with a larger range of possible fracture heights. In this example, the fracture height can be constrained by knowing the net pressure. Since the short height fractures have much larger widths to generate the measured tilt, they have correspondingly high net implied net pressure. In Figure 6, lines of constant implied net pressure in the plot are shown as black contours. Using additional data to further constrain the solution is not possible in all cases, but often proves a useful technique.

Discussion

Although the decision of which type of uncertainty analysis to use is generally clear-cut, there are rare cases where both the measurement and the modeling uncertainty are large. This might occur if tools are close to the fracture, but some unexpected noise source results in poor signal to noise ratios. Luckily there is some overlap between the two methods. If the theoretical tilt does not change much as fracture dimensions change, then a small perturbation in the measured tilt in the Monte Carlo analysis may steer the inversion routine to a different solution, increasing the calculated uncertainty. Similarly, measurements with poor signal to noise ratios generally result in a poor fit to the theoretical tilt, which increases the range of solutions that could possibly fit the data in the error map method.

What Does All This Mean to My Tilt Measurements?

After performing more than 10,000 hydraulic fracture tiltmapping procedures, calculated average uncertainties have led to reasonably accurate predictions of expected tiltmapping precision.

For Surface Tiltmapping, normal uncertainty in fracture azimuth is less than 1 degree per 1000 ft of depth and normal uncertainty in fracture dip is about ¼ of that.

For Downhole Tiltmapping from an offset wellbore, normal uncertainty in fracture height and length is about 10%–15% of the distance between the fracture and the monitor well at closest point of approach, so the closer the frac gets to the monitor well without going past, the better the precision.

Pinnacle experts prioritize the critical fracture measurements for a fracture mapping project along with maps, well logs and treatment designs to determine the best technology to measure what is most critical to our clients for each individual application.

"Close Enough" may be good for government work, but not for Pinnacle as we continue to refine our measurement technologies, our modeling techniques and our fracture mapping certainty.

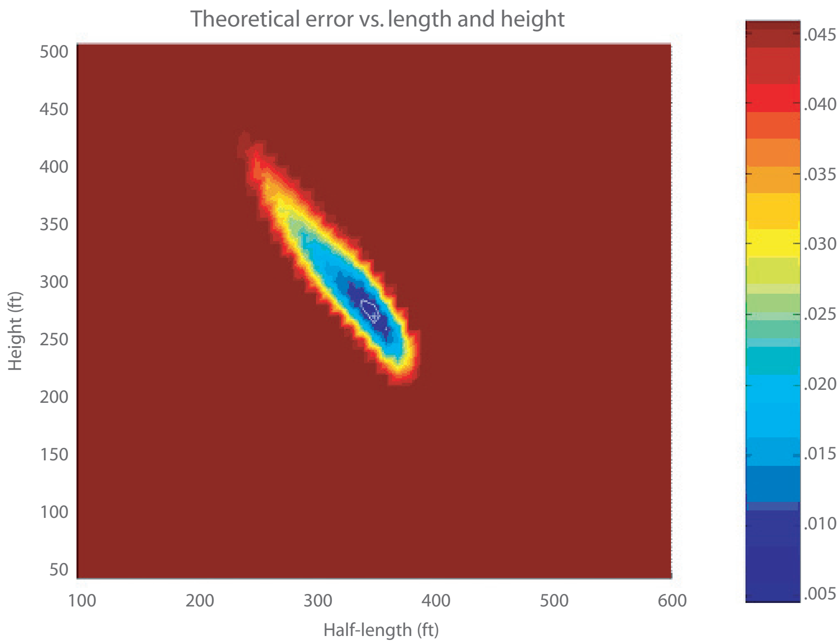

Figure 5. Fit error between measured tilt in an offset wellbore and theoretical tilt of fractures with different lengths and heights. Each modeled fracture also has a different width (not shown), optimized to match the data as well as possible. White cross and white outline show the point of minimum error and the possible solution space for the fracture dimensions as constrained by the tilt measurements.

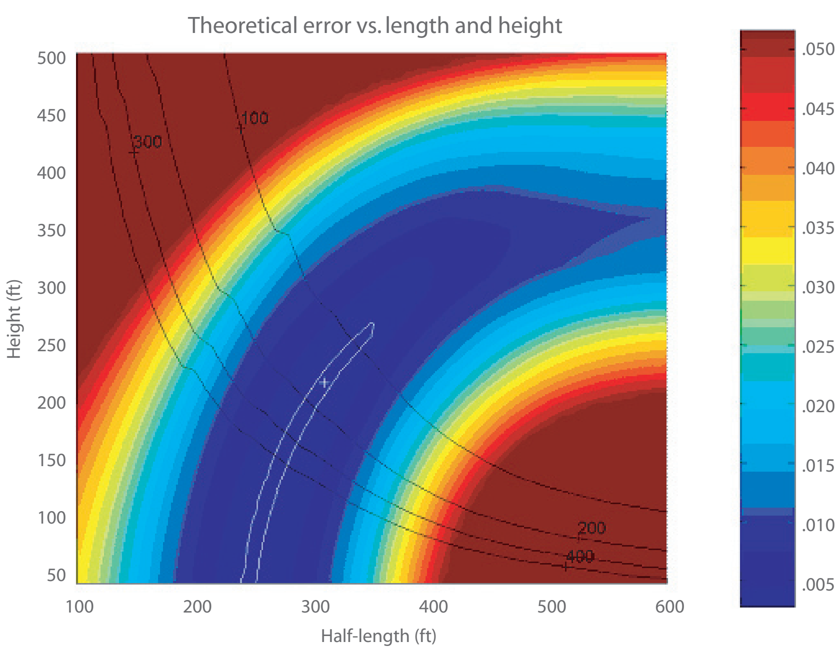

Figure 6. Fit error between measured tilt in an offset wellbore and theoretical tilt of fractures with different lengths and heights. Each modeled fracture also has a different width (not shown), optimized to match the data as well as possible. Black lines show contours of constant implied net pressure based on the fracture geometry. White cross and white outline show the point of minimum error and the possible solution space for the fracture dimensions as constrained by the tilt measurements.

Houston
281–876–2323

Denver
720–344–3464

Calgary
403–516–2260

Bakersfield
661–335–7711

San Francisco
415–861–1097

Dallas
972–401–0090

Delft
31–15–219–0062

Moscow
7–495–781–4820

Beijing
86–13838562150

Oklahoma City
405–604–5634

Midland
432–386–6791

Reynosa
52–892–42191

Cairo
2025283356–8

www.pinntech.com