The Evolution of Tiltmeter-Based Reservoir Monitoring: From Risk Mitigation to Production Optimization

S Marsic* (Pinnacle, a Halliburton Service), M. Machovoe (Pinnacle, a Halliburton Service) & W. Roadarmel (Pinnacle, a Halliburton Service)

Introduction

Tiltmeter technology has proven extremely valuable in heavy oil recovery fields as shown by the increasing installations worldwide, a 15+ year history of monitoring success in regions such as the San Joaquin Valley in California, and now an increasing regulatory demand for its operational use. The use of tiltmeter diagnostics has been a widely accepted tool for mapping of fracture stimulation treatments, but also fulfills a need for a cost effective, near real-time reservoir surveillance tool in thermal enhanced oil recovery (EOR) environments. Tiltmeter-based reservoir monitoring serves as an early warning system for out of zone steam migration and as a diagnostic to help improve operating and recovery efficiency.

Theory and Method

Nearly every reservoir-level process generates and propagates outward a pattern of strain that can be detected using sensitive deformation monitoring technologies. Tiltmeter-based reservoir surveillance has been successfully used throughout the world for nearly 20 years to precisely monitor fracturing stimulation-induced rock deformations which are then used to infer hydraulic fracture orientation and geometry (Wright et al. 1998; Davis et al. 2001). In a similar way, changes in reservoir volumes, such as those produced by fluid production, injection, and thermal processes such as steam flooding, Cyclic Steam Stimulation (CSS), Steam Assisted Gravity Drainage (SAGD), and CO2 Sequestration (CCS) also generate unique and measurable patterns of formation deformation (Du and Olson 2001; Du et al. 2008). These patterns, or deformation fields, can be measured at the earth’s surface with an array of tiltmeter instrumentation. By solving a geophysical inverse problem, precisely measured surface deformation can be used to solve for reservoir-level strain changes (Figure 1). By bringing the surface deformation measurements down to the reservoir level to identify and characterize fluid migration pathways, volumetric strain, pressure fronts, or even the thermal fronts, operators and asset managers are able to improve their understanding of how different storage and recovery methods work in different types of reservoirs at a significant cost savings over traditional monitoring technologies.

The primary goal of many tiltmeter-based microdeformation deployments is risk mitigation, specifically identifying, characterizing and reporting on out of zone fluid migration (Davis et al. 2000; Marsic et al. 2011). Beyond identifying these events, microdeformation diagnostics work in concert with other wellbore measurement devices such as flow and pressure gauges, seismic/microseismic mapping, distributed temperature and pressure sensing (fiber optic) and radioactive tracer surveys. These supplemental technologies can help identify damaged wellbores or extensive reservoir damage and paint a more complete picture of fluid, temperature and pressure changes within the reservoir. Benefits of this combined approach in EOR environments result in overall cost reduction, reduced mechanical failures, and improved production economics.

A secondary goal of tiltmeter-based reservoir monitoring has been realized by many operators once they began focusing on their recovery strategy in an integrated fashion with identifying and controlling out of zone EOR injection activities. CAPEX and OPEX costs associated with EOR steam generation are quite expensive. Maintaining fluid conformance within target zones and preventing out of zone fluid growth all have economic costs associated with them as ultimately this is lost money for a given project. Injecting into non-producing sands, contacting a common zone with multiple injections or losing steam to a pressure sink also affects project economics. The geomechanical inversion of surface-based reservoir monitoring diagnostics can provide a cost effective way to evaluate the performance of EOR projects by providing information for engineers...
and asset managers to react to and make more informed operational decisions. Traditionally, wells that produce the most oil are prioritized on the steam injection list. Tiltmeter-based reservoir monitoring best practices now dictate equal consideration for wells that create the most surface deformation (as a result of out of zone steam migration) and wells that are known communicators (with other wellbores and stimulation zones) with the most prolific producing wells when injections are scheduled. Operators can now fully realize the potential of pushing the injection envelope since a comprehensive understanding of the reservoir and subsurface fluid behavior allows them to optimize injection and production with their respective effects on the surface (dilation and subsidence). The long term impacts of these daily injections are also considered since the constant heating and cooling of thermal injection wells cause undue strain to wellbore materials with consequences eventually leading up to potentially expensive casing or cement failure. The formerly blind steam emplacement and fluid balance calculations can now be managed through improved modeling techniques by measuring the surface deformation and strain calculations. Through this novel approach utilizing tiltmeter data and keeping a close eye on net fluid balances, zones of significant subsidence or heave can be monitored and reversed by altering the injection and production cycles. Optimizing these injection cycles to minimize well strain will reduce the workover costs as well as reduce well abandonments that would normally be required once the reservoir and well damage is permanent. By accurately identifying damaged well casings, zones with damage can be squeezed out with cement rather than abandoned if caught in time.

Within this paper a case study (Field A) is presented where daily tiltmeter results play an integral role in helping engineers and field operators keep on top of cyclic well steaming strategies both in a risk mitigation and production enhancement capacity. Tiltmeter results not only highlight regions where shallow events may be occurring, they are able to detect out of zone growth within hours of steam initiation and identify potential source well candidates. If significant time can be saved in identifying problem areas, more resources can be applied to strategically moving steam around the field in a way that enhances overall production levels at a reduced fluid injection cost. The premise here is that the overheating of one area versus the under stimulation of another area often goes undetected, thereby increasing OPEX without realizing maximum recovery of the asset. Tiltmeter-based microdeformation monitoring serves to change this dynamic.

Tiltmeter-based microdeformation techniques often work best while in concert with other technologies. To bring additional value to the existing tiltmeter deployment, Field-A was equipped with Differential Global Positioning System (GPS) monitoring as well as a satellite-based Interferometric Synthetic Aperture Radar (InSAR) campaign to enhance the results provided by the existing reservoir monitoring operation. Three continuous survey grade GPS stations were installed to provide millimeter-level 3-D motion observables for tiltmeter and InSAR integration and data correction (Davis et al. 2008). InSAR deliverables are processed and delivered on a periodic basis to provide broad aerial surveillance over the field as well as to provide insight into deformation along and beyond the margins of the tiltmeter array where out of zone event activity may be undetected. As with the tiltmeters, all GPS and InSAR microdeformation diagnostics and geomechanical analytics are integrated, analyzed, and reported to the operator of Field A for further evaluation of current operations.
Figure 1. Example of a one-month tiltmeter based deformation output at Field-A used to track surface elevation changes (top). Ground displacement observations on up to an hourly basis are obtained from the field via automated radio telemetry for daily evaluation and analysis. Results can be presented in a variety of formats, database entries, GIS and interactive 3D visualizations (bottom).

Conclusions

It is important to highlight that there is no one “silver bullet” for monitoring complex reservoir-level processes. As with any technology there always are drawbacks and limitations. However, when deployed correctly and in the right environment, microdeformation monitoring has proven to be a reliable and cost effective methodology for obtaining information on reservoir behavior which can greatly help mitigate risk and improve operational efficiencies.
Acknowledgements

The authors thank Eric Davis, Zeno Philip and Tony Singh at Pinnacle for their input and project support.

References


