GRC Transactions, Vol. 42, 2018

Measuring Formation Strain to Determine Hydraulic Connectivity Using Fiber Optic Distributed Acoustic Sensing

Nicky Oliver[1], Michael Bruno[1], Julia Diessl[1], Kang Lao[1], Matthew Becker[2], Thomas Coleman[3]

[1]GeoMechanics Technologies

[2]California State University, Long Beach

[3]Silixa LLC

Keywords

Geothermal, Strain, Fiber Optics, Acoustic Sensing, Hydraulic Connectivity

ABSTRACT

Advanced methods in reservoir characterization are required to effectively harness geothermal energy from fractured high-temperature crystalline rock. It is critical to determine sufficient fluid connection between water influx and production wells to enhance thermal recovery and optimize the lifetime of the reservoir. GeoMechanics Technologies, in collaboration with California State University, Long Beach (CSULB) and Silixa LLC, is working in cooperation with the Department of Energy, Small Business Innovation Research through DOE SBIR Grant No: DE-SC-0017744 to investigate the use of fiber optic Distributed Acoustic Sensing (DAS) to improve geothermal reservoir characterization.

We use DAS to measure inter-well dynamic strain in response to periodic injection. The attenuation and phase lag between injection stress and strain are used to determine hydraulic connectivity in fractured bedrock. Fiber optic distributed sensing technology is capable of withstanding high temperature and pressure conditions typical of geothermal reservoirs. This tool would provide nearly continuous dynamic strain and temperature monitoring along the length of the wellbore, providing knowledge into hydraulic pathways even where perforations do not exist. Also, real-time measurements can be obtained throughout the lifetime of the well, ideally accounting for any changes in operations or reservoir configurations or thermally induced changes in permeability.

The objective of this research effort was to investigate and document the use of fiber optic DAS for measuring the hydromechanical response caused by fracture dilation in a reservoir and determine how that correlates to reservoir connectivity. Our team has successfully performed

numerical simulations, laboratory testing, and a field demonstration to further validate the effectiveness of DAS technology for detecting formation hydraulics.

1. Introduction

Short-circuiting of fluid circulation is the bane of all cold-water reinjection operations for geothermal energy recovery. GeoMechanics Technologies and partners have performed preliminary research to develop an innovative tool that could provide a basis for adaptive control of circulation in geothermal fields while they are under operation. The use of fiber optic DAS technology, which uses inter-well pressure sensing in response to periodic offset injection, may provide the means to determine hydraulic connectivity in fractured geothermal reservoirs.

Tracer tests are commonly used to estimate hydraulic connectivity in fractured geothermal reservoirs, but this method can be costly and time-consuming. Typically, tracer tests can last weeks or more and incur costly operational and analytical expenses. Tracer testing is also not depth specific, leaving it impossible to know which depth horizons contribute most to the tracer response in an open hole well. Also, tracer testing is usually only performed at the beginning of production for a new well, under the then-specified reservoir configurations and only provides insight into the connectivity for established extraction intervals. Fiber optic DAS could provide a means to detect true three-dimensional mapping of hydraulic connectivity in real time at any depth in the reservoir, throughout the lifetime of the reservoir.

Measuring hydraulic pressure changes in offset wells in response to periodic injection is an alternative indicator of hydraulic connectivity (Sun et al., 2015). However, conventional electric pressure sensors are incapable of operating under conditions associated with geothermal activity (temperatures greater than 200°C and pressures greater than 150 MPa). DAS has recently been demonstrated to sense fracture strain response to pressure oscillations of less than 10 Pa (Becker et al., 2016), and the technology uses a fiber optic cable that can be designed to withstand temperatures greater than 600°C (Mondanos et al., 2015) and pressures typical of geothermal reservoirs (Reinsch, 2008 and Paulsson et al., 2014). Because DAS measures instantaneous strain rate for the entire length of cable (Daley et al., 2015), hydraulic connectivity can be established at any depth along the wellbore within a 10 m gauge length resolution. A schematic of the system is shown in Figure 1. This tool would provide nearly continuous pressure monitoring along the length of the wellbore, providing knowledge into hydraulic pathways even where perforations do not exist. Real-time hydraulic monitoring can be performed without interrupting normal field operations. Also, measurements can be obtained throughout the lifetime of the well, ideally accounting for any changes in operations or reservoir configurations or thermally induced changes in permeability. DAS for hydraulic monitoring would offer a relatively inexpensive and robust tool to increase knowledge of geothermal reservoir connectivity as it can operate using existing fiber optic wellbore installations that were previously deployed for Distributed Temperature Sensing (DTS) or DAS seismic or acoustic monitoring.

GeoMechanics Technologies and partners have recently completed a research project performing numerical simulations, laboratory testing, and a field demonstration to further validate the effectiveness of DAS technology for detecting formation hydraulics. This paper focuses on the experimentation and results of the numerical modeling and laboratory testing.

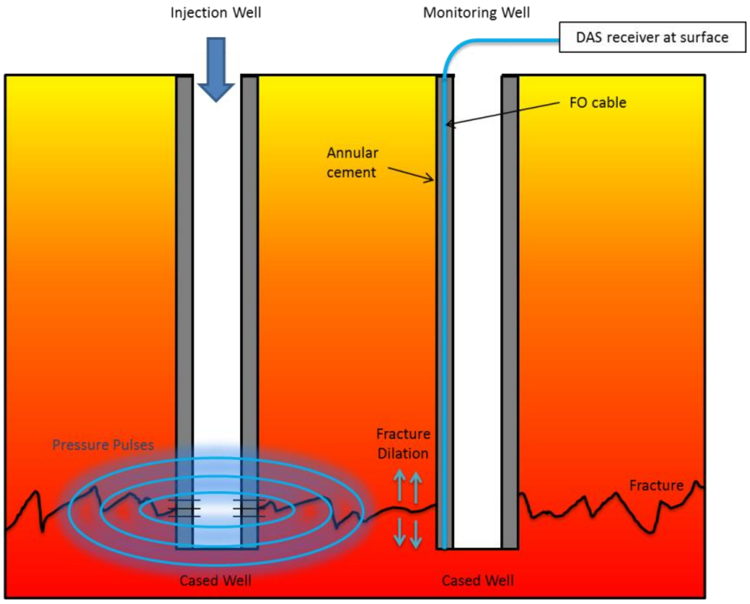


Figure 1: Schematic of fiber optic DAS system setup for pulse injection testing.

2. Methodology

This technology was tested using numerical modeling and was demonstrated in the laboratory and the field. We performed numerical modeling to better understand the strain response to pressure changes caused by fluid flow. A set of coupled fluid flow and geomechanics reservoir scale models were developed and applied under varying permeability and injection pulse scenarios. A near wellbore scale model was developed to test the transfer of formation strain through the wellbore construction. In the laboratory, we demonstrated that the DAS system measures fiber strain that can be linearly related to mechanical strain on a fiber optic cable. We also demonstrated that strain can be transferred through cement and fiber optic cable construction to be measured by DAS. Field testing was performed in the Los Angeles area and provided insight into some of the operational variables and construction limitations that can affect DAS data collection in the field. Since we anticipate testing the DAS technique more extensively in a more applicable geologic setting in the near future, this paper will focus solely on the results from the numerical modeling and laboratory investigations.

2.1 Numerical Modeling

2.1.1 Model Development

The objective of the numerical modeling was to develop three dimensional reservoir scale and near-wellbore scale simulation models to evaluate the relationship of pulse injection and offset stress and strain changes for a fractured reservoir. First, we wanted to verify that under conventional injection conditions, changes in pressure and strain at a designated offset location occurred at a resolution that could theoretically be detected through DAS technology. To accomplish this, a three dimensional reservoir scale numerical model was developed using a finite difference modeling (FDM) approach. To model fluid flow and mechanical interaction with dynamic coupling, the software code FLAC3D (Itasca, 2012) was used. A schematic of the reservoir scale conceptual model is shown in Figure 2.

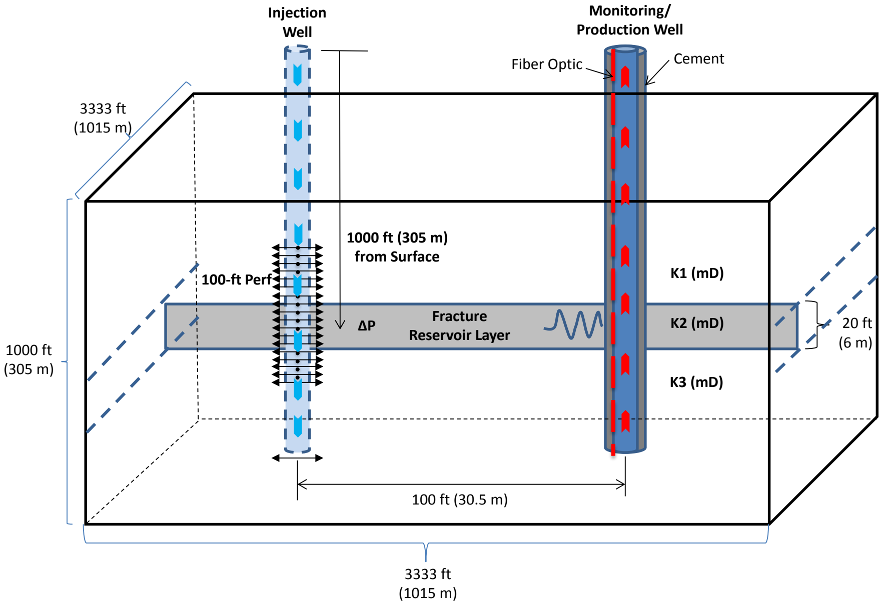
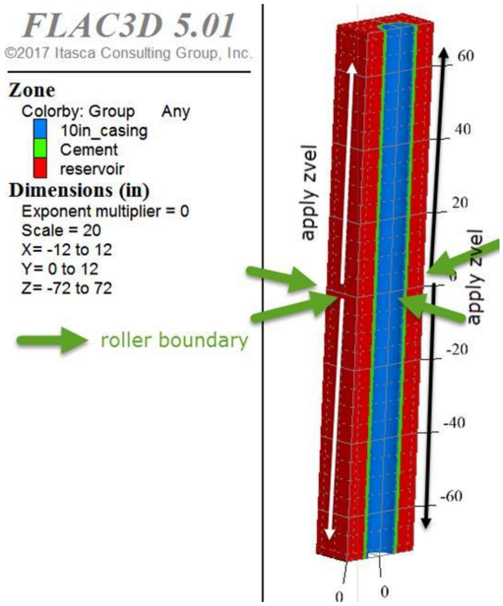


Figure 2: Reservoir scale conceptual model setup representing a geothermal reservoir with DAS technology to study induced stress and strain due to injection at an offset well location.

Next, we set up a refined near wellbore model using strain extrapolated from the reservoir scale model to analyze how strain is transferred through the wellbore construction. The objective of this modeling effort is to determine if formation strain is still detectable at the location of the fiber optic cable between the cement and casing. A conceptual model of the near wellbore scale model with variations in Young’s Modulus for cement and hole size were simulated, see Figure 3.



	E_{cement} (GPa)	HoleSize (in)
3Dn-Sim01 (baseline)	9.5	12.25
3Dn-Sim02	9.2	12.25
3Dn-Sim03	5.4	12.25
3Dn-Sim04	12	12.25
3Dn-Sim05	9.5	16.25
3Dn-Sim06	9.5	20.0
3Dn-Sim07	9.5	5.0

Figure 3: Conceptual model of the near wellbore scale model, and its simulation matrix.

2.1.2 Simulation Results

Application of the three-dimensional reservoir scale numerical modeling indicated that a high permeability zone inside a crystalline rock reservoir induces an identifiable strain pattern along vertical monitoring lines away from an injection well in response to low frequency pressure pulses (Figure 4). The order of magnitude of strain observed at a distance of 100 ft from the injection well ranged from nanostrain to microstrain depending on rock stiffness and permeability. This is well within the detectable range of DAS monitoring, as shown in our laboratory experiments and prior field experiments (Becker et al., 2017 and Becker et al., 2018). As expected, Figure 5 shows that the strain wave front travels faster than the pressure wave front. Figure 6 plots the sequence of the evolution of lateral strain over time passing through the monitoring well for Sim09.

The results of the near wellbore scale model indicate that all simulations showed a reduction of applied strain by two orders of magnitude. The ratio of the cement to reservoir stiffness influences the magnitude and axial distribution of transferred strain. Therefore, it is expected that a dampening in formation strain will occur as strain is transferred through the annular cement to the DAS fiber optic cable as shown in Figure 7.

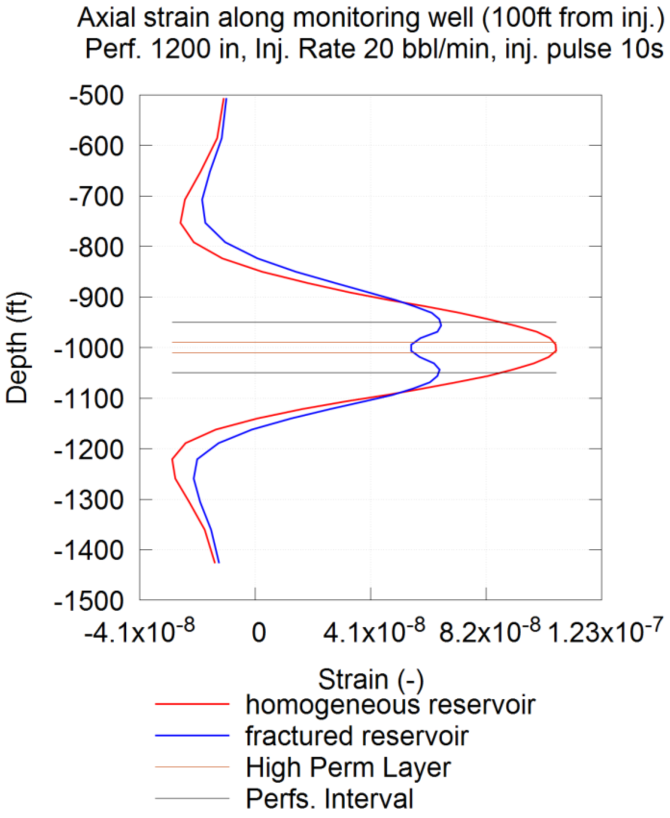


Figure 4: Axial strain along observation well for homogeneous and fractured reservoir about 15 min after a 10 s pulse.

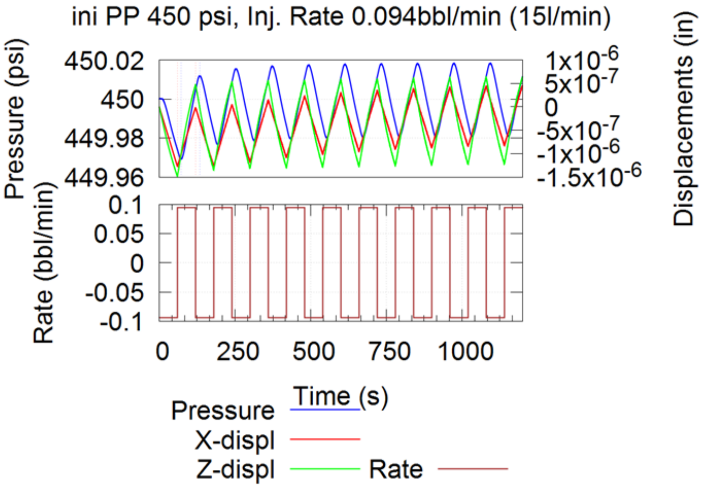


Figure 5: Pressure and displacement history at monitoring well for a 3D simulation assuming 200 mD uniform permeability.

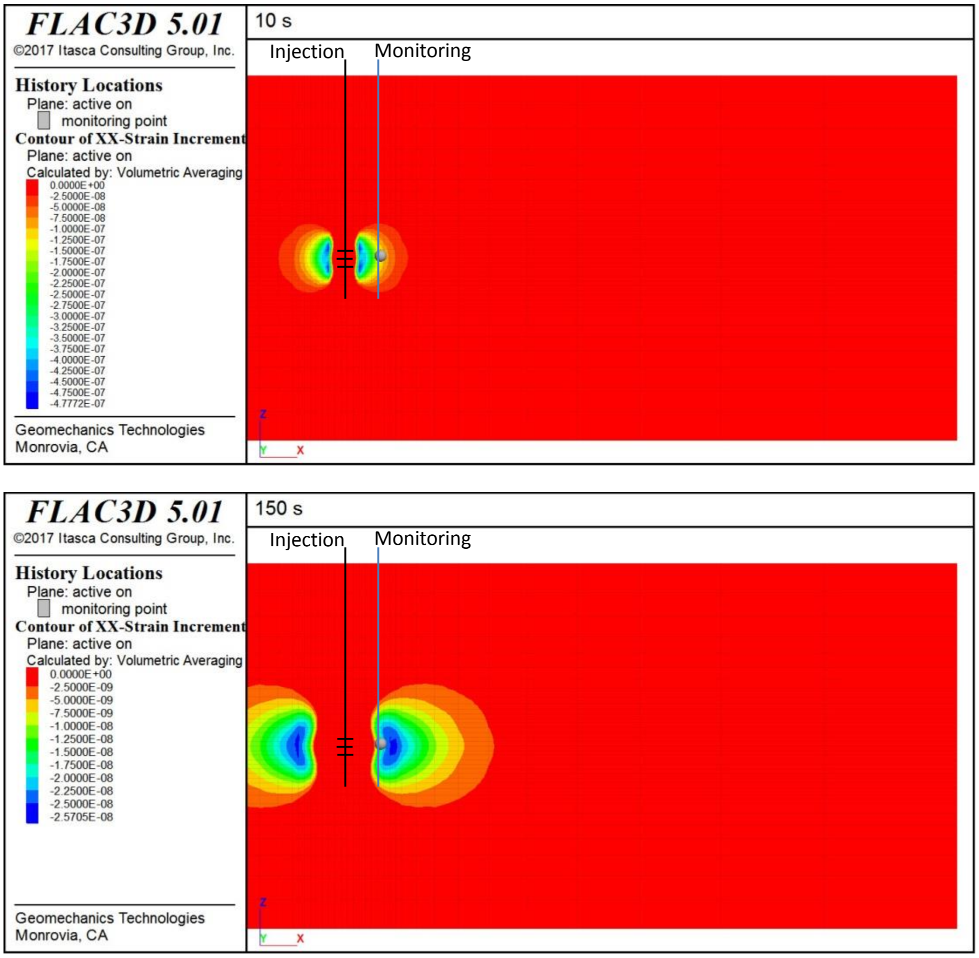


Figure 6: Vertical cross-section contour plots of lateral strain evolution and transient at 10-s and 150-s (Sim09) due to pressure pulse.

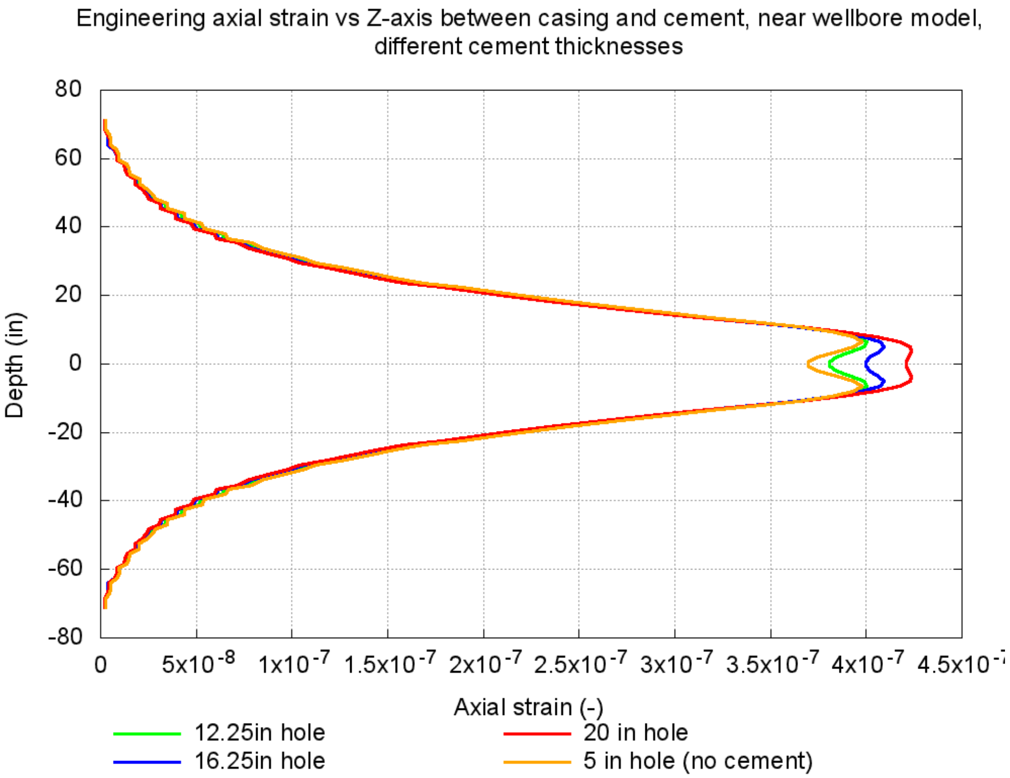


Figure 7: Induced axial strain along the casing for variable cement coverage.

2.2 Laboratory Strain Analysis

Two laboratory experiments were used to evaluate the ability of DAS to measure low-frequency strain on fiber optic cable. The first Cement Core Experiment evaluated the influence of cable construction on strain transfer. The second Fiber Strain Experiment verified that DAS-measured strain is linearly related fiber strain.

2.2.1 Cement Core Experiment and Results

The laboratory experiment was designed to mimic, as closely as practical, strain measurement on fiber optic cable embedded in a cemented borehole. An image of the experimental apparatus is shown in Figure 8. Five types of fiber optic cable were centralized and cemented into a 5 cm diameter clear PVC pipe and strained using a bracket operated by a stepper motor. A standard Class G borehole cement was used, and the inside of the PVC pipe was scored with a wire brush to ensure bonding. Strain was accomplished using a pair of specially machined aluminum brackets driven by a stepper motor. Strain was also measured using a DVRT strain meter with a 10 nm resolution (Lord Sensing, NANO-G-DVRT-0.5). The strain meters were mounted on a separate, outer pair of brackets clamped onto the PVC pipe. The entire apparatus was placed on rollers for a frictionless mounting.

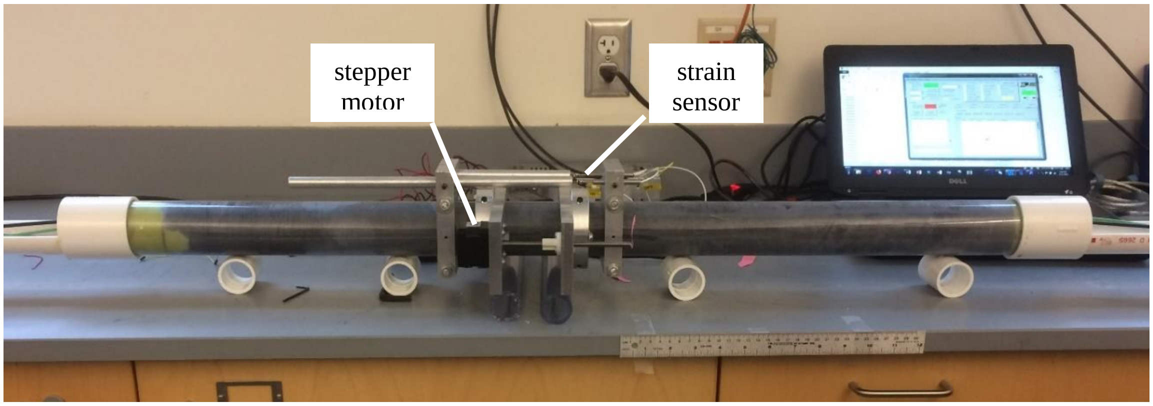


Figure 8: Experimental apparatus for testing fiber strain in cemented core.

Dynamic strain rate was measured on fiber optic cables using a Silixa iDAS^{TM} system. Sampling rate was 1 kHz and a strain measurement was reported every 25 cm. DAS measures strain on a fiber optic cable through interference of laser backscatter at two locations separated by a gauge length. The measurement gauge length was 10 m for this experiment, but strain occurred only between the two brackets separated by a distance of 8 cm. The five cables were spliced in series into a single length to allow simultaneous measurements on all cables. Additional fiber was added between the tested cables to prevent overlap between strain measurements in each tested cable. Five fiber optic cable designs were tested (Figure 9):

1. 900 µm OD tight buffered 9/125 µm single-mode fiber: This fiber was selected as a baseline as the polymer buffering is directly coated on the optical fiber.

2. 1/8” double stainless-steel tube with encapsulation: This cable is a common design for downhole installations, including geothermal.

3. 5.5 mm four-channel tactical: This all-dielectric tight-buffered cable contains two 50/125 µm multimode and two 9/125 µm single-mode fibers, aramid strength members, and a polyurethane jacket. This cable construction is commonly used for surface or shallow direct burial applications.

4. Fiber-in-metal-tube (FIMT) with steel wire armor/armored steel tube: This rugged design is commonly used for borehole distributed sensing applications and contains two 50/125 µm multimode and two 9/125 µm single-mode fibers within a gel filled FIMT surrounded by stainless steel armor wires. The cable is then encapsulated with HDPE.

5. Specialty strain and acoustic sensing cable: This design incorporates a single 9/125 µm single-mode optical fiber into a small diameter FIMT filled with a coupling resin to maximize strain transfer from the FIMT to the fiber. The FIMT is encapsulated with a polyamine outer sheath.

A dependence of strain on cable design is clearly visible in the DAS response. Figure 9 shows the amplitude of strain rate in response to the periodic stress imposed by the stepper motors. The ordinate scale should be considered arbitrary in this plot as strain rate has not been converted to strain. However, the relative responses will hold also for strain. The cable constructions described above are indicated in Figure 9. Cable 1 is considered the most accurate measurement of strain in the cement core due to its small diameter and because the glass fiber is directly buffered in flexible polymer material. Cable 4 is a realistic design for geothermal applications and demonstrated a loss of about 40% of strain measurement. Surprisingly, Cable 5, the specialty strain-sensing FIMT cable, did not perform significantly better than standard gel filled FIMT construction (Cable 4). We plan to deploy Cable 3 as a reference measurement and Cable 4 as a practical design at our future field site demonstration.

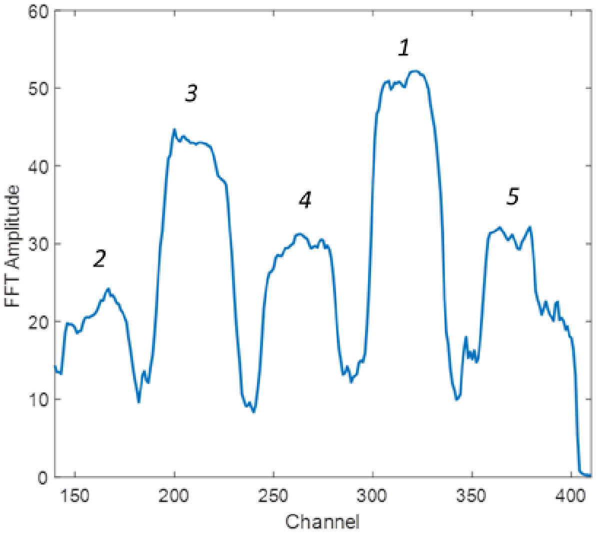


Figure 9: Relative strain rate responses from cables cemented into the artificial "core". The numbers correspond to the cable types explained in methods. The FFT amplitude units should be considered arbitrary.

2.2.2 Fiber Strain Experiment and Results

A laboratory experiment was conducted to strain a fiber without effects of surrounding cement or restricting cable construction. The rationale was to induce as closely as possible a "true" strain on the fiber with which to calibrate the DAS strain measurements. The 900 μm OD tight buffered 9/125 μm single-mode fiber (Cable 1) was chosen for this experiment as a baseline "bare" fiber scenario. The fiber was mounted into aluminum brackets and the length of fiber between the two mounts was 35 mm. Two synchronized linear actuator stepper motors were used to drive the separation of plates. The fiber was strained using four amplitudes of displacement: 5, 10, 14, and 20 μm.

DAS-measured displacement varied linearly with the mechanical displacement as induced by the stepper motor (r^2=0.99). At present, we are working with the data to understand how instrument parameters affect the measurements.

The linearity between the DAS and mechanical displacements is very encouraging. It indicates that the DAS is capable of measuring displacement on fiber optic glass if properly calibrated. The laboratory work demonstrates that the iDAS system is correctly measuring low-frequency dynamic strain and, consequently, can be used to accurately measure formation strain if the cable construction is calibrated in the laboratory.

3. Conclusion

GeoMechanics Technologies and partners have investigated the use of fiber optic DAS for measuring the hydromechanical response caused by fracture dilation in a reservoir and how that correlates to reservoir connectivity. Our research project consisted of performing numerical simulations, laboratory testing and a field demonstration in the Los Angeles area.

The significant findings from our research include:

1. From the numerical simulations using conceptual models, it is concluded that a high permeability zone inside a reservoir induces an identifiable strain pattern along vertical monitoring lines away from an injection well in response to low frequency pressure pulses.
2. The order of magnitude of strain observed at a distance of 100 ft from the injection well ranged from nanostrain to microstrain. Such strains are detectable with DAS technology currently available to industry.
3. Results of near wellbore scale modeling indicate that all simulations involving variations in Young Modulus of cement and hole size showed a reduction of applied strain by two orders of magnitude.
4. Laboratory experiments stressed the importance of cable design and installation in the field. Laboratory testing demonstrated that the DAS is capable of measuring displacement on fiber optic glass if properly calibrated.

Our results were encouraging and indicate that DAS technology may improve geothermal reservoir characterization. Two objectives remain to be accomplished before proceeding to commercial application: (1) demonstrating that fiber can be mechanically coupled to rock formations through borehole cement and (2) explaining how hydraulic transmissivity can be related to these strain measurements in boreholes. We plan to apply for future funding to accomplish the first objective through field experiments at a bedrock test site or active geothermal field site. We will accomplish the second objective through three-dimensional hydro-mechanical simulation, benchmarked to the field experiments.

Acknowledgment: This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Award Number DE-SC-0017744.

REFERENCES

Becker, M. W., Ciervo, C., Coleman, T., A Slimhole Approach to Measuring Distributed Hydromechanical Strain in Fractured Geothermal Reservoirs, *Proceedings: 43rd Workshop on Geothermal Reservoir Engineering*, Stanford, California, February 12-14 (2018), SGP-TR-213.

Becker, M. W., Ciervo, C., Cole, M., Coleman, T., Mondanos, M., Fracture hydromechanical response measured by fiber optic distributed acoustic sensing at milliHertz frequencies. *Geophysical Research Letters*, (2017), 44, 14, 7295-7302.

Becker, M.W., Cole, M., Ciervo, C., Coleman,T., Mondanos, M.J., Measuring Hydraulic Connection in Fractured Bedrock with Periodic Hydraulic Tests and Distributed Acoustic Sensing, *41st Workshop on Geothermal Reservoir Engineering*, Stanford, CA (2016), SGP-TR-209.

Daley, T., Miller, D.E., Dodds, K., Cook, P., Freifield, B.M., Field Testing of Modular Borehole Monitoring with Simultaneous Distributed Acoustic Sensing and Geophone Vertical Seismic Profiles at Citronelle, Alabama, Geophysical Prospecting, (2015), doi: 10.1111/1365-2478.12324.

Itasca, FLAC3D - Fast Lagrangian Analysis of Continua in 3 Dimensions - Theory and Background, Minnesota, Itasca Consulting Group Inc., (2012).

Paulsson, B.N.P., Toko, J.L., Thornburg, J.A., Slopko, F., He, R., Development and Test of a 300°C Fiber Optic Borehole Seismic System, *Proceedings: 39th Workshop on Geothermal Reservoir Engineering*, Stanford, CA (2014), SGP-TR-202, edited.

Reinsch, T., Prospects and Limitations of a Distributed Temperature Measuring System for the Deployment in Hot Geothermal Wells [Master's thesis]: University of Cologne, (2008).

Sun, A.Y., Lu, J.M., Hovorka, S. "A Harmonic Pulse Testing Method for Leakage Detection in Deep Subsurface Storage." *Water Resources Research*, 51, 6, (2015), 4263-4281.