SAND2017-10997R

Sandia National Laboratories

2017 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY

Summary: Laboratory Evaluation of EGS Shear Stimulation

1. Laboratory Evaluation of EGS Shear Stimulation

- Organization or Affiliation: [1]Sandia National Laboratories/ Geomechanics Research
- Principal Investigator: Stephen Bauer
- Contact information: email: sjbauer@sandia.gov; Ph: 505-844-9116
- Participating Orgs.: Ahmad Ghassemi, Kai Huang, Qinglu Cheng, University of Oklahoma, P. Barrow, Sandia

- Project Start and End Date: October/2013 – September/2016

2. Project Objectives and Purpose

The objectives and purpose of this research has been to produce laboratory-based experimental and numerical analyses to provide a physics-based understanding of shear stimulation phenomena (hydroshearing) and its evolution during stimulation. Water was flowed along fractures in hot and stressed fractured rock, to promote slip. The controlled laboratory experiments provide a high resolution/high quality data resource for evaluation of analysis methods developed by DOE to assess EGS "behavior" during this stimulation process. Segments of the experimental program will provide data sets for model input parameters, i.e., material properties, and other segments of the experimental program will represent small scale physical models of an EGS system, which may be modeled.

The coupled lab/analysis project has been a study of the response of a fracture in hot, water-saturated fractured rock to shear stress experiencing fluid flow. Under this condition, the fracture experiences a combination of potential pore pressure changes and fracture surface cooling, resulting in slip along the fracture. The laboratory work provides a means to assess the role of "hydroshearing" on permeability enhancement in reservoir stimulation. Using the laboratory experiments and results to define boundary and input/output conditions of pore pressure, thermal stress, fracture shear deformation and fluid flow, and models were developed and simulations completed by the University of Oklahoma team. The analysis methods are ones used on field scale problems. The sophisticated numerical models developed contain parameters present in the field. The analysis results provide insight into the role of fracture slip on permeability enhancement-"hydroshear" is to be obtained. The work will provide valuable input data to evaluate stimulation models, thus helping design effective EGS.

3. Project Timeline (with milestones and/or decision points, as applicable)

This project was initially funded in FY14.

- Complete analysis based experiment design and select feasible experimental paths forward. In parallel, complete a portion of the first series of experiment(s) incorporating induced fractures. Tests will include fluid flow measurements at elevated temperatures and pressures (temperatures to be determined through analyses). Parallel analysis and experimental work effort will help improve progress. January/31/2014
- Develop experimental methods. This includes adaptation/development of high temperature (175C), high confining (representative) pressure (13.7 MPa), and pore water pressure flow through system. Complete first experiments at high temperature and pressure flow-through unfractured rock specimens. Results from the experiments were used to provide feedback to improve experimental design, experimental conduct, and data collected in the second series of experiments. June/30/2014.
- Develop/iterate on numerical analyses methods to assess experimental boundary conditions in the context of experimental system and experimental input and output for unfractured experiments. Develop understanding of sensitivities. July/30/2014.
- Deliver GO/NO GO reporting and SKYPE presentation to DOE GTO, August/15/2015

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- Develop experimental, and in parallel, numerical analysis methods for fractured samples. Implement methods at high temperature (175C), high confining (representative) pressure (20.7 MPa), and high temperature pore water pressure flow through system. Complete first experiments high temperature and pressure flow through fractured rock specimens. These are samples received of natural fractures granite from Colorado School of Mines. Results from the experiments will be analyzed to provide feedback to improve experimental design, experimental conduct, and data collected in the second series of experiments. February 2016.
- Develop analysis methods and complete numerical analyses of initial fractured sample tests. Analyze experimental results for conditions of slip July 30/2016.
- Analyze, integrate, experimental/numerical results in the context of project goals develop publications. September/30/16

4. Technical Challenges/Barriers

- The test system, although an adaptation of an existing system, was modified for this test series and presented a challenge to conduct these long term tests and obtain meaningful data.
- Modeling of the test system, although “simple” in geometry included a significant amount of detail leading to complex meshing and modeling.

5. Technical Approach

For EGS, self-propping shear stimulation, sometimes called hydroshearing, of existing fracture networks is one method of sub-surface permeability enhancement being investigated by the DOE. Water injected (below the level of the least minimum stress) into a stressed fractured rock system may cause existing fractures to dilate and slip in shear due to a combination of the in situ stress state and the local temperature changes due to water injection, etc. An objective of this task is to provide modelers with data used/needed for simulations of EGS through controlled laboratory experiments guided by analyses. Aspects of these phenomena have been observed in the field and attempts have been made to model system attributes of such. Given the large number of variables in the EGS physical systems, a fundamental understanding of operative mechanical, thermal, and hydrologic processes in a controlled laboratory environment is warranted.

We engaged in an experimental/numerical analysis study to effect of flowing water through a hot stressed fracture in a rock. We developed a test system for this purpose. The test system was comprised of a cylindrical rock sample with a fracture (initially smooth surface and later a natural fracture oriented at ~30^{o} to the cylinder axis) with flow access holes to and from the fracture. The water-saturated-lead-jacketed sample was confined, heated to 175C, and subjected to a differential (shear) stress. Pore pressure was varied in tests performed allowing us to vary the effective normal stress on the fracture. During a flow test, the downstream pressure was decreased a small amount, 0.7 to 1.5 MPa (100 – 200 psi), and the pumping system moved room temperature water through the specimen to maintain the pressure boundary condition. For certain stress conditions, the specimen was observed to displace along the fracture surface.

The University of Oklahoma collaborated in this effort, developing and completing analyses to (1) design the experiments to meaningfully represent an EGS, (2) select and position instrumentation to collect appropriate material property information for analysis, (3) provide necessary insight into interpretation of experimental results based on their detailed modeling of the thermal/poroelastic/mechanical response of the experimental system, and (4) assess experimental results to provide meaningful data for subsequent EGS related analyses.

This project leveraged other non-EERE DOE investments. An advanced multiplexor system for the near simultaneous measurement of acoustic emissions and seismic velocity was recently developed with DOE BES funding and we attempted to use it in this study. The DOE nuclear waste program has invested funds in the refurbishment of the creep frames necessary for the tests that were performed.

6. Technical Accomplishments

Experimental System Development– An existing pressure vessel and loading frame was modified/adapted for data acquisition and control (DAS) for extended time periods at confining pressure, temperature, and pore pressure (month-long test time frames) at high temperature (175C), high confining (representative) pressure (20.7 MPa), and high temperature pore water pressure flow through system on samples nominally 3' in diameter and 6" long. The test system/sample assembly may represent one Five samples were successfully tested, data recorded and results submitted to the data repository.

Numerical Analyses – The primary purpose of our modeling effort is to consider key physical processes. Due to significant different physical mechanisms for fractured and intact rock, different methods are employed. For intact porous rock, thermo-poro-elastic model is employed to capture the coupling effects of displacement, porous flow and thermal diffusion. To capture mechanical response of a fracture surface to simulate the flow and slip, a coupled thermo-poroelastic interface element model is used. An algorithm was adapted to generate the interface element mesh from a continuum mesh geometry. To capture the mechanical response of the fracture, a zero thickness contact element model is used. Then, a fictitious thickness is assigned to the original geometry of the zero thickness interface element to generate a volumetric interface element needed for transport processes of flow and thermal diffusion in the fracture. The fluid flow and thermal conduction in the fracture are modeled by a volumetric interface element model. We developed numerical analyses methods to assess experimental boundary conditions in the context of experimental system and experimental input and output for unfractured experiments. The numerical analysis portion of the project involves simulating rock sample (Westerly granite core specimen) response to fluid injection. Initial phase modeled the problem considering poroelastic response, and coupled thermal process are currently simulated. The specimen is discretized into 34366 hexahedral elements and 36563 nodes. In subsequent analyses, thermo-poroelastic response is examined by considering the temperature difference between the injected fluid and rock specimen. The sample has an initial temperature of 175° C and the temperature at its sides is fixed. During the simulation, the heat source at the upstream borehole is hold at 21.7° C. All other conditions are kept the same as the initial poroelastic case. Simulation of experiments show the model can capture relevant processes.

7. Challenges to Date

The experimental system is complex, time consuming and tedious to setup and conduct; small oversights and minor clogs to the flow system are costly in time. The experiments proved too electrically noisy to collect meaningful acoustic emission data. The numerical models contain many elements and nodes and were challenging to construct and run.

8. Conclusion and Plans for the Future

A lab-based test system to experimentally evaluate hydroshearing has been successfully developed and several experiments, of EGS-type pressure, temperature, and stress conditions, have been completed to demonstrate the phenomena. Sophisticated numerical analysis methods have similarly been successfully developed and applied in simulations of the complex coupled thermal-mechanical-hydrological phenomena associated with the lab tests. It appears that the thermal-mechanical perturbation resulting from flow of cool water through a hot stressed fractured rock can cause slip. A reasonably good correlation between measured response and models was realized. The value of the analysis/lab study was the ability for testing and analysis researchers to interact in near real-time.

9. DOE Geothermal Data Repository

Lab results are in spread sheets submitted to the DOE Geothermal Data Repository (http://gdr.openei.org/). Analysis results are in papers presented/published AND in **dissertations completed**.

10. Other Dissemination of Research: N/A

- Strong collaboration between Sandia and University of Oklahoma: 2-3 PhD students matriculated

11. Publications and Presentations, Intellectual Property (IP), Licenses, etc.

Bauer, S. J., K. Huang, Q. Chen, A. Ghassemi, P. Barrow, *Laboratory and Numerical Evaluation of EGS Shear Stimulation*, PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering, Stanford Univ., February 22-24, 2016, SGP-TR-209

Bauer, S. J., K. Huang, Q. Chen, A. Ghassemi, P. Barrow, *Experimental and Numerical Investigation of Hydro-Thermally Induced Shear Stimulation*, 50th US Rock Mechanics / Geomechanics Symposium, 26-29 June 2016.

Ye, Z., M. Janis, A. Ghassemi, S. Bauer, *Experimental Investigation of Injection-driven Shear Slip and Permeability Evolution in Granite for EGS Stimulation*, PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Eng., Stanford Univ. Stanford, CA, Feb. 13-15, 2017

Huang, K., Q. Cheng, A. Ghassemi, S. Bauer, *Evaluation of Stimulation by Shear Slip in Fractured Rock Using a 3D Coupled Thermo–Poro-Mechanical FEM*, submitted to refereed journal