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Controlled Permeability Enhancement in the Near Well Field Using "Smart" Cyclical Pulses

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ABSTRACT

Key to most geothermal applications is ensuring that there is high enough subsurface permeability within the reservoir for the overall operation to circulate fluid without excessive pressure gradients or parasitic energy costs whilst maintaining a workable temperature. The permeability of the near well field is particularly dominant in both dictating the fluid connection to the far field reservoir, and the connection to natural preferential flow features, such as fractures as part of a fracture and discontinuity network. Being able to enhance the near well field permeability is therefore extremely valuable, reducing the costs of the fluid circulation operation and potentially accessing larger areas of the reservoir pore space. Soft cyclical stimulation techniques present an opportunity of being able to enhance near well field permeability without causing significant microseismic hazard. By managing pulse stimulation frequencies using smart feedback, we demonstrate, through both experimental work and modelling, how it is possible to control the superposition of pulses within the borehole. By using the physical phenomena of pulse superposition to create enhanced pulses, the surface working pulse pressure remains well below the fracture pressure of the rock, and thereby increases the borehole life as well as reducing the overall risk of unexpected microseismic events through pressure spikes. The repeated application of these enhanced pulses can lead to the growth and development of new fractures, and the increase in shear movement thereby mismatch along existing fractures. The combined effect of these processes should lead to a significant enhancement of the near well permeability and an enhancement in the productivity of wells.

1. INTRODUCTION

Geological engineering encompasses a range of applications from resource extraction (hydrocarbons, geothermal heat and power, water) to waste disposal (carbon capture and storage, wastewater disposal) and energy storage (compressed air, hydrogen). All of these technologies rely on pumps to move fluid into or out of boreholes. The pumps used in well stimulation are often used in very simple ways to deliver a known pressure to the top of the wellbore, leading to inefficient processes that produce a lot of traffic, noise, emissions and waste. Cyclic Soft Stimulation (CSS) has been proposed as a way of reducing induced seismicity around stimulated wells (Hoffman et al 2018 and references therein), increasing the complexity of induced fracture networks (Zhou et al 2017), and improving well productivity (Ciezobka et al 2016). However the scientific and technological understanding of pulsed well stimulation is currently limited. For example, the most appropriate combinations of mean and varying stress magnitudes and frequency are poorly understood and the most appropriate methods of engineering these unsteady loadings at the far end of a wellbore has not been established. Our *Smart Pulses for Subsurface Engineering* partnership vision of CSS invokes using rock fatigue at frequencies of a few Hertz to reduce breakdown pressures. This paper details a range of fundamental investigations required to understand 1) the optimal time-dependent pressure loadings on rock volumes, 2) the material response to dynamic loading of the system that is being pumped: the rock mass and the borehole (casing and cement), 3) how the pressure loading is influenced by the well hydraulics during wellbore operations under transient conditions 4) how the time-dependent operation of a well system can be engineered, and 5) monitor rock mass response to develop fully 'closed loop' control systems.

2. CHARACTERISING ROCK FATIGUE

Understanding the rupture of geomaterials is integral to geothermal energy extraction. Of particular importance is the time- and rate-dependence of material strength, which impacts fracture architecture and thus hydraulic conductivity and system permeability. This behaviour contributed to the development of cyclic soft stimulation (CSS) techniques to maximise resource extraction whilst minimising large amplitude fluid-injection induced seismicity. A series of laboratory experiments have been conducted to investigate the potential benefits of applying cyclical hydraulic pressure pulses to enhance the near-well connectivity through hydraulic fracturing treatment. Such experimental constraints are essential to inform cyclic stimulation practices for subsurface engineering.

A pump has been developed to create cyclical square pressure pulses which have been applied to laboratory experimental boreholes in large 20x20cm polyaxial cylindrical samples (Fraser-Harris et al, 2020a). This equipment has been used to perform pulsed-pumping experiments in PMMA (used in the literature as an analogue for shale), as well as Granite G603. In addition to stress and pressure sensors, these experiments have been instrumented with fibre optic cables for high resolution circumferential strain measurements. The transparent PMMA was also instrumented with optical recordings of fracture development, while the brittle granite was instrumented with acoustic transducers for measurement of acoustic emission events. These novel large-scale, high-resolution experiments were complemented by indirect tensile measurements and cyclic fatigue Brazilian disc testing at a range of peak loads and cycle amplitudes, demonstrating that weakening by cyclic hydraulic pressurisation mimics relationships defined by conventional fatigue testing of geomaterials.

The impact of cyclical hydraulic pressure pulses on the number of cycles to failure in PMMA and G603 have been measured under unconfined conditions. Using cyclic square pressure waves, breakdown pressure was reduced by up to 15% compared to the monotonic case in G603, and 25% in the PMMA. These significant reductions in breakdown pressure could be expected to minimise the occurrence of large induced seismic events when compared to monotonic fluid injection. Furthermore, they suggest that cyclic pressure pulses could require lower power and water consumption relative to monotonic fluid injection.

The peak pressure of the oscillations provided the primary control on the total power and number of cycles to failure. However, increasing the minimum cycle pressure in the borehole (and therefore, increasing the mean pressure) further reduced breakdown pressure, suggesting that even small pressure fluctuations during hydraulic stimulation may reduce the possibility of the largest stress drops, and hence the magnitude of induced seismic events. Circumferential strain measurements detected accelerating precursory deformation a few cycles prior to failure during the experiments in granite, suggesting that activity could potentially be monitored and controlled in real-time during field geothermal production.

Cyclic pressure pulse trials at elevated in-situ stress conditions are ongoing using the University of Edinburgh's GREAT cell apparatus (McDermott et al. 2018). Cyclic pressurisation at in-situ conditions (equivalent to 500m depth) has been found to impact the breakdown pressure of PMMA similarly to the effect measured at ambient conditions. The impact of in-situ stress conditions on monotonic fluid injection experiments in G603 has been recorded, and pulse pumping experiments are ongoing under these conditions. The GREAT cell apparatus offers the unique possibility to investigate the fluid transport properties of the resulting fracture network under varying true-triaxial stress state post-breakdown (Fraser-Harris et al. 2020b) and the resulting conductivity field compared to the strains measured around the borehole using the fibre-optic sensors.

3. SIMULATING FATIGUE DEGREDATION IN HETEROGENOUS ROCKS

It is clear that the soft cyclic stimulation induces fatigue of rock to reduce the breakdown pressure and potentially the associated risk of seismicity. However, the mechanism for cyclic stimulation-induced fatigue of rock is rather unclear and prior to this research there was no implementation of fatigue degradation in modelling the rock response under hydraulic cyclic loading. To elucidate the pulse-induced fracture mechanism of rock, numerical modelling can provide unique insights given the difficulties in conducting large-scale pulsating hydraulic fracturing experiments. To accurately simulate the fracture process of rock under hydraulic pulses, it is important to first understand the fatigue mechanisms and develop rational constitutive model to account for the fatigue-induced strength reduction. We also need to understand the response of heterogenous rock to the hydraulic pulse by considering the heterogeneity in nature fractures, different minerals, etc. Moreover, advanced numerical framework and algorithms are necessary to simulate the nonlinear damage process which is also computationally expensive.

In our work, we have developed both linear and nonlinear fatigue models for rocks. In the linear fatigue model (Xi et al., 2021), we have formulated the fatigue degradation based on *S-N* curves (*S* for cyclic stress and *N* for cycles to failure) and implemented into the constitutive relationship for fracture of rock using in-house FORTRAN scripts and ABAQUS solver. We have used a cohesive crack model to simulate the discrete crack propagation in rock which is coupled with hydraulic flow and pore pressure capability. We have validated the numerical model via the experimental results presented above. A new loading strategy for pulsating hydraulic fracturing was proposed. Using this new loading protocol, a slow and steady rock fracture process was simulated while the failure pressure was reduced.

In the nonlinear fatigue model (Xi et al., 2022a), a cyclic cohesive zone model (CZM) for low-cycle fatigue of quasi-brittle materials was developed. Irreversible displacement induced by the low-cycle fatigue was considered in the cyclic CZM. The fatigue and static damage variables were used for irreversible displacement accumulation and stiffness degradation, respectively. A nonlinear fatigue damage model was then proposed to calculate the fatigue damage in the cyclic CZM. The fatigue damage parameters were determined based only on experimental S-N data and the fatigue damage evolution derived from the fatigue model was compared with that from experimental results. Further, the developed cyclic CZM was implemented into ABAQUS solver by a VUMAT subroutine. The developed cyclic CZM provides the first tool for low-cycle fatigue crack modelling of quasi-brittle materials.

Near-wellbore rock fracture is a key subject in subsurface energy extraction and is of particular interest of our research. While many geothermal wells use open hole completion, it may be more appropriate under specific rock conditions to use perforated well casing. The effects of the combined casing-cement-rock well system on pressure transmission in fracturing the rock have not been sufficiently addressed, and is key to understanding some important phenomena such as fracture tortuosity. We have developed a combined analytical-numerical model to investigate the rock fracture mechanism near the wellbore with realistic consideration of the boundary condition imposed by the complete well system (Xi et al., 2022b). Different well configurations can lead to variation in the pressure applied on the rock formation and thus affect the fracture propagation near the wellbore. Our results show, as the stress transmission through the casing and cement into the rock is enhanced, the fracture propagates at an angle closer to the perforation orientation and at the same time the breakdown pressure is increased. At greater distances from the perforation, the crack is eventually deflected towards the maximum in-situ principal stress direction. The near-well tortuosity of the crack is considerably influenced by the well design, in-situ stress condition and perforation length. The developed model can be used to aid decision making in terms of improved understanding of hydraulic fracturing technology and well design optimization.

The heterogeneity induced by natural fractures in rocks also plays a significant role in controlling the fracture process. To simulate the interaction between the hydraulic fracture and the natural fractures, a mixed-mode fracture model able to cope with large confining pressure is needed. We have developed a mixed-model fracture model considering Mohr-Coulomb criterion in modifying the shear fracture behaviour under large compressive normal stress (Xi et al., 2022c). In this model, the shear fracture properties are dependent on normal stress and frictional coefficient. Near-wellbore interaction between the hydraulic fracture and natural fracture was modelled by considering the effect of wellbore on stress re-distribution, e.g., evacuation effects, and radial fluid pressure acting on the wellbore.

Three interaction modes including crossing, deflecting and offsetting were demonstrated and analysed to examine the effect of near-wellbore heterogeneity on fracture growth.

4. DELIVERING THE CYLIC PRESSURES WITIN THE WELL

In order to be able to utilise fatigue failure of rock, there needs to be a system at the surface to deliver the required cycles to the wellhead and account for damping of the signals as they travel down the well. This will require novel hardware to enable the efficient generation of cyclic pressures at specific locations in a borehole that is many hundreds of metres long. Rather than uniformly cycling the pressure across the entire length of the borehole, the approach we have developed is to engineer a novel form of controlled water-hammer (i.e., superposition of pressure waves) that enables the location of pressure peaks to be controlled by a digital control system.

There are four strands to the investigation:

(i) Modelling: The development of computational models to represent pressure wave behaviour in well pipe systems and to assess that behaviour in full scale and small-scale systems,

(ii) Control: The development and theoretical validation of a pulse generation concept involving pulse control to augment fatigue loading at targeted spatial locations,

(iii) Integration: The integration of optimal control algorithms and pulse generation methods to augment pressure pulse loadings,

(iv) Validation: The design of a laboratory scale facility to validate the pulse generation concepts.

Three scenarios have been investigated involving (i) pulse generation (ii) pulse generations with passive dissipation and (iii) pulse generation with active elimination, with the main findings as follows;

(i) An optimised duty cycle where pulses are generated (no dissipation or elimination) can successively achieve constructive interference of the pressure pulses at a targeted location in the pipe. A disadvantage is that a spatially distributed cyclic pressure variation in a specific mode shape also occurs along the pipe. With the specific application in mind (rock fracturing) this occurrence would possibly lead to structural integrity issues in the pipeline.

(ii) An optimised duty cycle where pulses are generated and passive dissipation is accounted for as part of the strategy can successively achieve constructive interference of the pressure pulses at a targeted location in the pipe. This operating strategy leads to significantly less cyclic pressure variation along the pipe.

(iii) An optimised duty cycle where pulses are generated and active pulse elimination is implemented can successively achieve constructive interference of the pressure pulses at a targeted location in the pipe with no subsequent cyclic pressure variation along the pipe.

Computational simulations of (iii) have suggested that this approach can successfully create down hole pressure cycles whose location in the bore hole are controlled by the coordinated movements of high-speed servo valves on the topside. To validate these simulations an experimental rig is being commissioned (Figure 1) that is designed to support the generation of targeted pulses, at frequencies up to 20Hz, at any point on the 200m long pipeline.

In summary, the project has created a hydraulic control system, whose simulation suggests that its implementation will enable the creation of cyclic pressures at locations remote from the pumping systems. The results of the experimental program to validate the simulation will be available in late 2023.

5. ENSURING SAFE OPERATIONS

Deploying an entirely new system of well stimulation requires an operator of a well to have confidence in the technology, therefore near-real time monitoring is required to unlock the deployment of soft cyclic stimulation. Microseismic monitoring has been extensively used to monitor dynamic changes within large rock masses and as a tool for monitoring stimulation processes for subsurface energy projects. Borehole networks offer increased sensitivity to small magnitude seismic events over surface-deployed networks, but they require drilling of boreholes and can be restricted in space. As a result, localisation accuracy of the recorded seismic events suffers. In Parastatidis (in review) we show that a surface network at a patch array geometry using only 12 seismometers can cover a similar rock volume in detecting events up to M-1.5 as a surface array of more than 100 seismometers. An additional advantage of this is the significant reduction in the size of the seismic recordings and as a result a shorter analysis time.

Manually detecting and distinguishing seismic recordings is challenging. Research on automated end-to-end denoising, detection, and classification of microseismic events, as an early warning system, is still in its infancy. To this effect, our work in Li et al (2021) is focused on jointly evaluating and developing suitable approaches for signal denoising, accurate event detection, non site-specific feature construction, feature selection and event classification. We propose an automated end-to-end system that can process big data sets of continuous seismic recordings very rapidly, and demonstrate its applicability and robustness to a wide range of events (distant and local earthquakes, slidequakes, anthropogenic noise etc.). Algorithmic contributions lie in novel signal processing and analysis methods with fewer tunable parameters than the state of the art, evaluated on two field datasets.

In order to consider seismic recordings from multiple channels and stations, a comprehensive and integrated seismic monitoring workflow is proposed in Li et al (2022) for continuous multi-channel recorded signals at an ongoing landslide, which consists of multi-channel event detection with linear coherency analysis via Multichannel Coherency Migration (MCM), graph-based feature weight optimisation and classification. Specifically, with the continuous recordings from multiple sensors in an array, the proposed system first detects potential events with the coherence analysis (i.e., MCM) of the multi-channels, and identifies the strongest signal components for feature construction. Then, we design graph-based feature weight optimisation for seismic event classification to detect and classify, in addition to earthquakes, seismic sources such as rockfalls and processes related to landslides (e.g., fissure formation) thereafter referred to as slide quakes. Additionally, after rigorous feature engineering analysis with a range of state-of-the-art feature-based classifiers, recommendations are provided for the best physical features to use in supervised and semi-supervised learning approaches in Li et al. (2022).

Novel supervised (Jiang et al., 2020) and semi-supervised (Li et al., 2022) machine learning approaches for automated detection (Li et al., 2020) and classification of seismic events have been developed and tested on seismic recordings from geologically distinct sites. The semi-supervised approach based on graph-based learning is ideal when the amount of data for training is relatively small, compared to the deep learning supervised approach. Both the graph-learning based semi-supervised and convolutional neural network (CNN)-based supervised learning algorithms have demonstrated that they can be transferable to new unseen datasets, e.g., from the geologically distinct active SuperSauze landslide in the Alps to Larissa in Greece, with different seismometer network geometries.

Having detected and classified recorded signals, fast and accurate location is necessary for the interpretation of the data and the underlying process. Parastatidis et al. (2021) present a waveform-based localisation approach that can provide in almost real time locations for small in magnitude earthquakes.

6. CONCLUSIONS

Overcoming technical and societal challenges that currently limit the use of subsurface resources requires re-engineering systems for enhanced efficiency, safety and public accountability. Traditional pumping systems used to fracture rock with high fluid pressures have simply supplied liquids into pipes and boreholes with little regard to their dynamic response. Indeed, engineers often only consider the dynamics of the system to avoid, diagnose or eliminate resonance phenomena (e.g. water hammer). Progress in fast processing, digitally controllable pumps and robust wireless sensing offers a major new opportunity to combine these to tailor pumping cycles to exploit and match the optimal dynamic behaviour of the receiving conduits (the pumped system). Our *Smart Pulses for Subsurface Engineering* partnership is developing the basic knowledge required to enable the creation of smart well stimulation systems where the action of the high-pressure pumps is adapted by real-time sensing and modelling to exploit the dynamic behaviour of rocks and wellbores. Our ultimate aim is a transformative technological development which increases production efficiency while reducing the environmental and societal impact of operations in geothermal, oil and gas and wider sectors. Integrating across rock mechanics, well engineering, hydraulic engineering and AI-informed signal processing has resulted in a genuinely whole-system approach to re-engineering well stimulation.

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