DESTRESS

Demonstration of soft stimulation treatments of geothermal reservoirs

Soft hydraulic stimulation. Best Practice Workflows & Tools for (design of) Hydraulic Stimulation

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Abstract

This report sketches a best practice for the design and modeling of soft hydraulic stimulation in enhanced geothermal system (EGS) applications. The description is given with the input from field tests performed within the context of the DESTRESS project. Specific issues are the setup of the operations, the modelling of reservoir performance and induced seismicity. For the modeling, an integrated workflow is proposed that combines the strengths of comprehensive numerical models, fast models for stochastic calculations, and Monte Carlo approaches for model calibration, optimization, and model-supported decision making. Important learnings are given from the post-mortem analysis following the M5.5 earthquake in Pohang in November 2017 and the seismic risk assessment before and updating during the cyclic soft stimulation treatment performed in Reykjavik in October 2019.

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1 Introduction

DESTRESS targets stimulation of Enhanced Geothermal Systems with minimal seismicity. This immediately poses an internal conflict: stimulation intends to activate a fracture network and consequently seismicity – at the same time the seismicity must be kept within safe and acceptable limits. Therefore, the concept of "Soft Stimulation" was invented to prevent large seismic events. One of the soft stimulation concepts is cyclic pumping. Clearly, such treatments require careful design, close monitoring, and insightful modelling. These issues are the subject of the present document. The main target is to lead the reader to more elaborate literature that was already around and that has been produced within the scope of the DESTRESS project. Within the DESTRESS project, the main activities in Soft Hydraulic Stimulation have been in connection with the Pohang site in Korea and the Geldinganes site in Reykjavik, Iceland. Therefore, much of the present document will refer to these field tests. The Pohang case also offers a very good opportunity for learning through the work performed after the M5.5 earthquake occurring months after completion of the stimulations in the field.

2 Best Practice for Design

The design of the EGS treatment in well PX-1 in August 2017 in Pohang has been adequately summarized by Hofmann et al. (2018). It includes different cyclic injection schemes, such as long-term cyclic injection, medium-term cycles and short-term cycles. Additionally, the pressure was managed by slow and stepwise pressure changes and low maximum pressures. Instead of shut-in, continuous injection was performed followed by flowback and the traffic-light system has been adapted for cyclic injection schemes. The traffic light system was set up with magnitude thresholds connected to different actions (continue as planned / reduce rate / stop injection / flow back). In case the targets of the treatment were not reached, re-injection or multi-stage injection could follow. Most importantly, the injected volume was limited by determining the site-specific relation between the injected net fluid volume and the maximum magnitude of induced seismic events. The deviation from this trend was identified as the maximum injection volume.

The results of the field operation are provided by Hofmann et al. (2019). The early treatments in Pohang had shown seismicity (e.g., Park et al. 2017), but the data has been inconclusive. Therefore, the fourth stimulation focused on improving the location of seismic clouds, which were intended as future drilling target. Much attention was given to limiting the seismicity to moment magnitudes Mw < 2.0. At the same time, a monitoring of the stimulation performance in real time was planned using harmonic pulse test analysis. The treatment schedule and monitoring system were tailored for these purposes. Overall, this soft stimulation treatment in Pohang was the shortest and used the lowest flow rates, pressures, and volumes as compared to the three treatments before and the one treatment after.

The injection scheme was based on the objective of soft stimulation: a limited injection volume and limited injection rates based on earlier fracture tests. Earlier seismic responses led to maximum duration of the injection cycles. Further, harmonic pulse tests were designed in order to follow the productivity enhancement in real time. Pulse test durations for these were based on expected effective permeability and on wellbore storage effects resolved from the well properties. Precision real-time injection rate and pressure monitoring were imposed to enable real-time control and later interpretation.

For the seismicity, a dedicated network was set up to be able to follow induced seismicity in terms of frequency, location, and magnitude. Care was taken to make the monitoring network good enough to detect magnitudes below 0. This was achieved by installing a 17-level geophone chain in the second deep well at the Pohang site in addition to the existing network.

Finally, the methods for data analysis were set up. For the hydraulic data, they included injectivity analysis to determine the fracture opening pressure in real-time; conventional well test analysis to determine the hydraulic performance of the well at low pressures; and harmonic pulse test analysis to determine the hydraulic performance of the well during high pressure injection. For the seismic data, they included methods of compilation of the seismicity catalogue, including location and magnitude estimation methods. Specifically, tube waves detected by the geophone chain could be used to improve location accuracy significantly. Real-time seismic data analysis was key to effectively manage the immediate seismic response of the treatment.

From the analysis following the earthquake in November 2017, more lessons can be learned (Lee et al, 2019). In particular, it became clear in hindsight that during drilling a large fault had already been activated: “Had the presence of the fault and its susceptibility to slip in the prevailing stress regime been recognized at the time, it would have been clear that injection in to PX-2 posed a substantial hazard and greatly increased the risk because of the proximity to Pohang.” Lee et al conclude that “Best practice involves a formal process of risk assessment, with input from competent authorities, and the updating of this assessment as knowledge of the potential hazard evolves. Implementation of a comprehensive risk framework should incorporate scenarios of a triggered large earthquake.”

The design of the soft hydraulic stimulation performed on the peninsula Geldinganes within the city limits of Reykjavik, Iceland, is summarized in Hofmann et al. (2020). First, the seismic risk was evaluated by assessment of historic seismicity in the region and by a comprehensive risk assessment that has been published before the start of any field operations by Broccardo et al. (2019). This study is the “first of its kind pre-drilling probabilistic induced-seismic hazard and risk analysis” and provides “probabilistic estimates of peak ground acceleration, European microseismicity intensity, probability of light damage (damage risk), and individual risk.” This a-priori risk assessment has continuously been updated during the field operations with in-situ data. A conventional seismic traffic light system has been complemented by this advanced traffic light system (Mignan et al. 2017, Grigoli et al. 2017). Seismicity was monitored by a continuous local network starting almost 1 year before the field operations. More temporal surface and borehole receivers were added during the treatment including a deep borehole geophone chain. This allowed detection of events well below magnitude 0 in real-time. Seismic data was openly accessible in real-time on the website http://veitur.isor.is/eqview/.

The concept was to stimulate multiple existing inflow zones by sealing off individual structures from the rest of the wellbore using inflatable straddle packers (multi-stage stimulation). Inflow zones (stimulation targets) and intact rock (to place the packers) were identified based on temperature logs, drilling data, caliper logs, borehole televiewer logs and other borehole geophysical data, such as neutron logs. Each stage was started with low flow rates that were slowly increased in steps until fracture opening was observed.

3 Best Practice to Model Observations

3.1 Earth Model

Reliable modelling of productivity requires appropriate input and physics-based, calibrated models. A study thus starts with a proper geological characterization. The publication by Park et al (2017) forms an example with application to Pohang (see Figure 1) – although the main fault causing the 2017 earthquake was not detected. A proper model includes the geological setting, formation temperatures, geomechanical properties, and flow properties. These fundamentally include possible faults and fractures, and the stress situation acting on them in order to assess the potential for activation, stimulation, and induced seismicity. The geological findings can be captured in a 3D geological model or in a more conceptual description. The decision to either of them should be led by the level of information available.

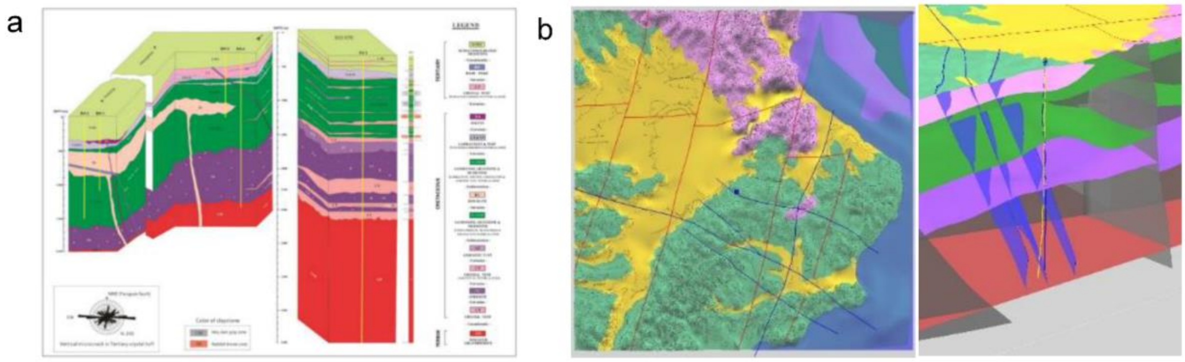

Figure 1 (a) 3D geological map of the Pohang area and (b) major fracture zone near the site (from Park et al, 2017)

The modelling of injection or production efficiency requires knowledge about the effect of stimulation through its mechanical and hydraulic response. Such models exist on different levels, which are complementary in nature (Grant, 2011). Full numerical models are available that couple 3D flow models to 3D mechanical models. An example is FLAC-TOUGH (Taron 2009), in which the two tools are coupled through a script that exchanges the information between them after each timestep. FLAC-TOUGH was also used for evaluating the response of EGS operations (Wassing et al, 2014, 2019, 2020). A more integrated approach is provided in OpenGeoSys, which is a single tool in which the equations are solved in an integrated manner (Kolditz, 2012). Parisio et al (2019) indeed employed OpenGeoSys to assess EGS and its risks in supercritical geothermal systems. The numerical tools, however, have two drawbacks when used for EGS. In the first place, they are often CPU intensive. Large computation times preclude their running with many realizations of input parameters. As a consequence, it is difficult to use them in a stochastic manner, which is required when there is considerable uncertainty in the input parameters or when calibration is required. In the second place, the required gridding is often time-intensive and precludes the application to many different geometric realizations, for instance when the orientation or location of faults is not well known. Still, the comprehensive coupled models provide the opportunity to gain understanding of the subsurface processes involved and to simulate specific cases in a detailed way. For Pohang, a TOUGH-FLAC model has been setup by Park et al. (submitted), a FRACMAN model was built by Farkas et al. (2018) and a GOLEM (Cacace and Jacquey 2017) model is currently being built. Similar studies will be performed for the Geldinganes site.

Faster models rely on analytical or semi-analytical solutions. These have inherent constraints, for instance a simplified geometry (e.g. homogeneous; axially symmetric; 2D) or simplified constitutive behavior. Within DESTRESS, a semi-analytic model has been developed that suffers not from all these limitations (Fokker et al, 2019; 2020). The most important constraints are that the model is currently formulated for plane strain conditions and axial symmetry. However, with respect to other semi-analytical models, it offers the additional capability of rather advanced constitutive relationships and at the same time time-dependent behavior to facilitate flow properties affected by cooling or stimulation. For the a-priori risk report of the stimulation in Geldinganes, a hybrid model was employed, where 3D numerical modeling of flow with a discrete fracture model (Karvounis and Jenny, 2016) is combined with stochastic modeling of seismicity (Karvounis et al., 2014). Potential hydro-shearing events are pre-sampled at several hypocenters and their source times are simulated with the flow model. This hybrid model can probabilistically forecast both of the induced seismicity during stimulation and of the thermal breakthrough during the production phase, when seismicity follows the Gutenberg-Richter distribution and planned injection occurs in a reservoir with known hydraulic effective properties (Karvounis and Wiemer, 2020).

We propose as a feasible workflow to combine the powers of fast and fully numerical models. In such a setup, the static earth model defined by the geology will first be translated into a fully numerical coupled dynamic model. This way, a typical case can be simulated. Then, the case is mimicked by one of the available simplified and fast models. A calibration could be necessary since the constraints imposed by the fast model might preclude a full resemblance. Once that has been done, the fast model can be used in a stochastic setup, as will be detailed below, in order to map the uncertainty of input parameters and the flexibility of operational choices to the corresponding outcome. The stressing-rate dependent seismicity approach that is outlined below (see Candela et al, 2017, 2018) can be employed to assess the associated risks.

3.2 Well Testing

Well testing is the standard technology to assess reservoir flow properties: permeability, skin, storage, and flow boundaries (Bourdet, 2002). These methods can naturally be applied to EGS operations with soft stimulation. A drawback of well test analysis, however, is that it is difficult to assess the reservoir response during production or injection. To address this issue, harmonic pulse testing is a possibility. It is easy to deploy and can be used during ongoing operations with minimal equipment. In addition, it is ideally suited for soft stimulation applications: the pulses that it requires can be the same as those employed for the soft stimulation itself. The technology was applied in Pohang and a detailed evaluation showed its feasibility (Salina Borello et al, 2019; see also Figure 2). Points of attention include the precise switching of the flow rates, the synchronization of measurements of flow rates and of pressures, and the interpretation.

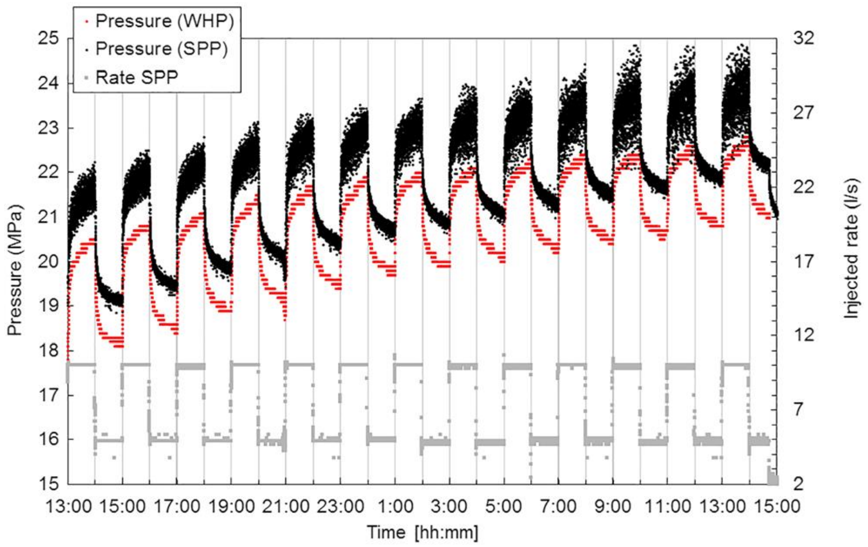

Figure 2 Pulse test on Pohang PX-1 during injection.

3.3 Seismic responses

Important learnings have been obtained after the earthquake in Pohang (Lee et al, 2019). They specifically addressed the importance of comprehensive and ongoing efforts to monitor, analyze, and understand the evolving seismic hazard, and of an open-access policy and clear channels of communication to maximize their contribution to the mitigation of seismic risk and to update information to the public authorities on the changing seismic risk conditions.

They also noted that models of earthquake nucleation do not adequately forecast the pre-mainshock evolution of a fault or the possibility of pressure perturbations triggering runaway slip. They pose that further work is required to develop physical and statistical models of induced and triggered seismicity to provide appropriate bases for risk assessment. One possible approach is to calculate the rate of change of stress according to Segall and Lu (2015). Candela et al (2017, 2018) have applied this approach to geothermal applications (Figure 3). They specifically note the importance of thermo-elasticity.

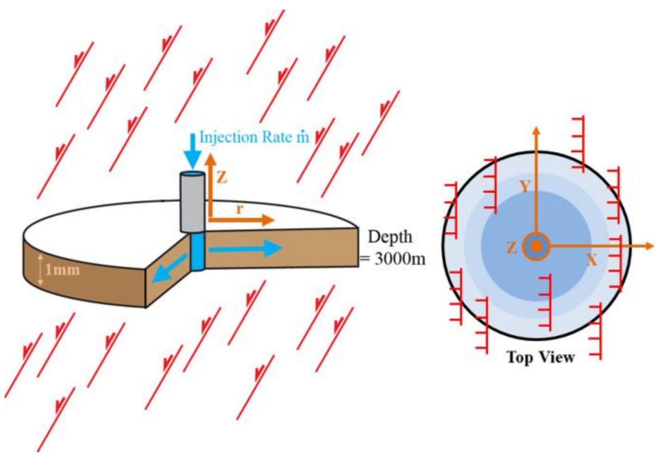

Figure 3 Model geometry for assessing thermally-induced stressing rates and associated seismic risks (Candela et al, 2018)

Another approach, developed during DESTRESS, is an analytical injection model through faults coupled with a physics-based block-spring type rupture model (Candela et al, 2019a,b). In doing so, each single induced event potentially triggered by the cold-injection at the faults and/or inter-events stress transfer can be modelled. The focus was specifically on honoring the fractal complexity of natural faults, known as having a prime influence on the spatio-temporal distribution of the induced seismicity (see Figure 4). The non-trivial interaction between the rate of injection, fault geometry, and inter-events long-range elastic interactions was explored. This fast approach is currently coupled with a data-assimilation scheme and applied to the recent stimulation performed at the Geldinganes geothermal site. Finally, one last approach is to explicitly model the stress development on identified faults. Van Wees et al (2019a,b) have devised a rather effective numerical scheme to do so without having to evaluate the geomechanical response of full modelling domain.

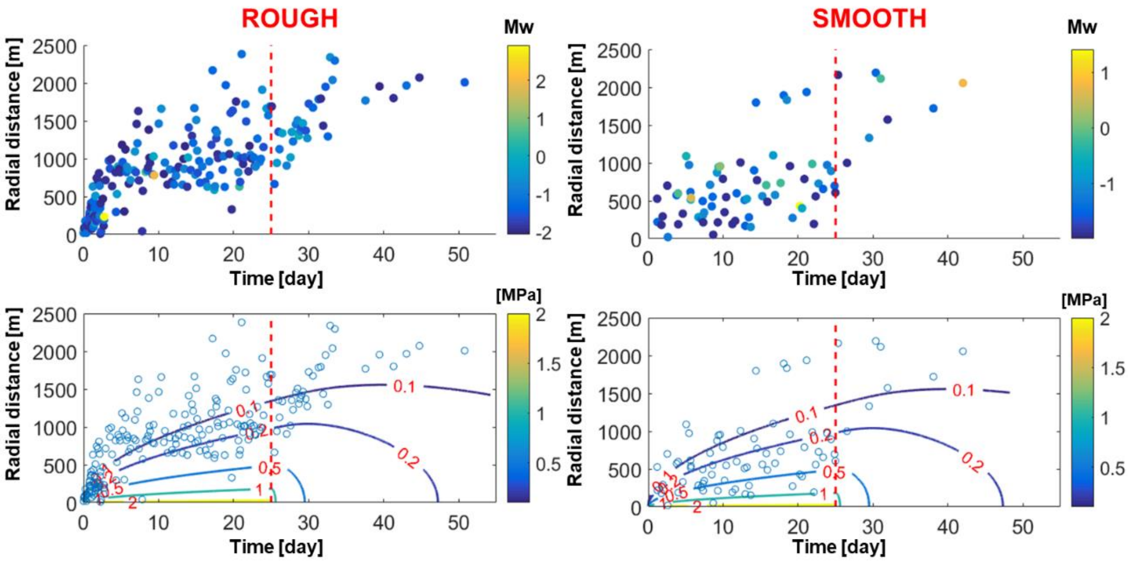

Figure 4 Effect of fault roughness on the spatio-temporal distribution of induced seismicity (Candela et al, 2019b)

Lee et al further note that, like in many projects involving injection of water to stimulate permeability, the emphasis of the monitoring program in the Pohang EGS project was on the avoidance of earthquake magnitudes that would breach traffic light system thresholds, rather than on obtaining accurate hypocenters and documenting the evolution of the seismicity sequence. This narrow focus meant that the evolving risk was neither recognized nor communicated. It is essential that EGS and related stimulation activities use a risk-based traffic light system that adapts to evolving hazards such as fault activation from multiple stimulations.

4 Best practice for sensitivity analysis and uncertainty assessment

Within the DESTRESS project, an extensive study was performed on Key Performance Indicators with the use of Monte Carlo simulation (Welter et al, 2019). The resulting workflow can be used as the overarching context in which decisions are made based on scientific knowledge including its uncertainty. Models for hydraulic stimulation can be fit into it. A performance assessment then can be accompanied by a quality measure in the sense of a range of expected outcomes, or the expected effect (including its range) of different operational choices.

The Monte Carlo study addresses the complete workflow and proposes an integrated Geothermal Energy model. Figure gives an overview. The model is organized in five different parts. As a starting point the input data set is fed into the model. This includes uncertain parameters i.e. risk factors, which are described with a probability density function. In the center of Figure the technical models are pictured. Between the single models only data on the physical state of the thermal water is exchanged. Starting from the reservoir model a closed loop is simulated. This includes the following:

- Drawdown in the production reservoir
- Temperature and pressure reduction in the production wellbore
- Energy utilization in the power/heat plant
- Pressure and temperature changes in the injection well
- Up arching in the injection reservoir
- Pressure coupling with production reservoir.

All technical models feed data into the economic model, where different cost engineering approaches are used to calculate costs, earnings and the different KPI. Uncertainty mainly caused by risk factors also plays an important role in the economic evaluation. Risk factors are often integrated into the model by using risk associated costs that put a burden on the economic results. The technical as well as the economic models use yearly time steps. Thereby the model is static on a short time step but dynamic over the whole observation period. Maintenance costs, a decrease of reservoir temperature or any other time dependent changes show their effect in specified/calculated time steps (=years). According to the rules of financial mathematics, all costs are discounted/compounded to the base year, which is the year with the first delivery of energy to customers.

For a detailed description of the components of the Integrated Geothermal Energy Model we refer to the report by Welter et al (2019).

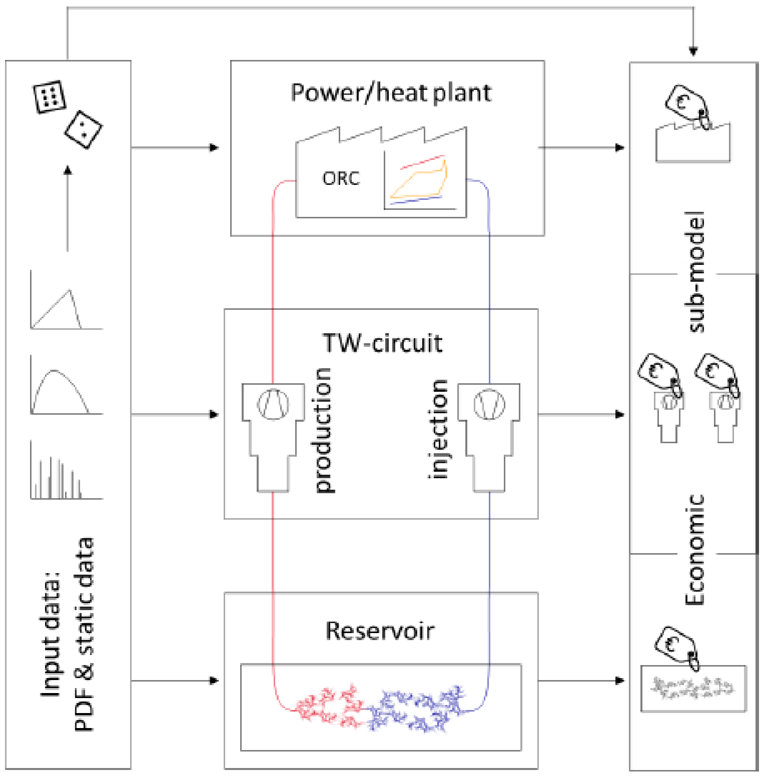

Figure 5 Model overview of the integrated geothermal energy model (from Welter et al, 2019)

5 Discussion and Conclusions

The sustainability of stimulation efficiency is an important issue. Increased injectivity or productivity that does not last will quickly make a stimulation operation uneconomic. However, there is presently very little experience with the sustainability of EGS projects. More experience and longer-lasting results are required to underpin the theoretical models, to develop models that forecast slowly varying reservoir properties, and to calibrate them with actual measurements.

We have provided a sketch for a best practice for the design and modeling of soft hydraulic stimulation in EGS applications. Specific issues are the setup of the operations; the modelling of reservoir performance; and induced seismicity. For the modeling, an integrated workflow is proposed that combines the strengths of comprehensive numerical models, fast models for stochastic calculations, and Monte Carlo approaches for model calibration, optimization, and model-supported decision making. Important learnings are given from the post-mortem analysis following the earthquake in Pohang in November 2017.

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Wassing et al, in preparation (2020) FLAC-TOUGH on Pohang

Welter et al, 2019. Key Performance Indicators with the use of Monte Carlo simulation

Appendix DESTRESS D6.2 – related publications

Broccardo, M., Mignan, A., Grigoli, F., Karvounis, D., Rinaldi, A.P., Danciu, L., Hofmann, H., Milkereit, C., Dahm, T., Zimmermann, G., Hjörleifsdóttir, V. & Wiemer, S. (2019). Induced seismicity risk analysis of the hydraulic stimulation of a geothermal well on Geldinganes, Iceland. Natural Hazards and Earth System Science, Discuss., https://doi.org/10.5194/nhess-2019-331, in review.

Candela, T., van der Veer, E. F., & Fokker, P. A. (2018). On the Importance of Thermo-elastic Stressing in Injection-Induced Earthquakes. *Rock Mechanics and Rock Engineering*, *51*(12), 3925-3936.

Abstract The sustainability of geothermal fields is based on a paradox. On one side, fractures are targeted on heat-flow improvement, and on the other side, the same fractures are avoided because of induced seismicity risk. In this context, we developed analytical approaches for estimating (1) thermo–poro-elastic stresses in a fractured geothermal system, and (2) seismicity rates based on the model of Dieterich (J Geophys Res 99:2601–2618, 1994). We modeled cold water injected at a constant rate into a single fracture surrounded by hot impermeable layers. The rationale for focusing on one single isolated fracture was that flow in the vicinity of injection wells is often concentrated in a couple of fractures instead of being homogeneously distributed. Heat flow appeared to be dominated by advection inside the fracture and conduction outside it. Poro- and thermoelastic stresses around the single fracture were estimated separately following two independent analytical approaches; and for any potential fault around the single fracture, the induced Coulomb stress rates were resolved. The role of thermal stresses appeared to be the leading one. We show that thermal-stressing rates can induce an increase in the rate of seismicity of more than a 1000-fold at distances up to 200 m from the single fracture. Our fast forward models are suitable for data assimilation and they open the route for heat-flow optimization while keeping seismicity at a relatively low magnitude.

Candela, T., Ampuero, J-P, Van Wees JD, Fokker, P. A., Wassing, B. (2019). Semi-analytical fault injection model: effect of fault roughness and injection scheme on induced seismicity. In *European Geothermal Congress, EGC.*

Abstract Our newly developed fault injection model for induced seismicity in the context of geothermal systems starts from the most constrained heterogeneous ingredient of the rupture model, that is the geometrical roughness of fault surfaces.

Synthetic fractal surfaces mapping real fault geometry are combined with an “instantaneous” slip-weakening model with spatially homogeneous static and dynamic friction coefficients.

Without introducing unconstrained frictional heterogeneities, multiple rupture events following the expected dynamic in terms of spatio-temporal distribution are generated. This rich seismicity’s dynamic emerges from the non-trivial interplay between pore pressure diffusion, geometrical heterogeneities of the fault surfaces and stress interactions between the successive rupture events.

Candela, T., Peters, E., Van Wees JD, Fokker, P. A., Wassing, B., Ampuero, J-P (2019). Effect of fault roughness on injection-induced seismicity. In *53rd US Rock Mechanics/Geomechanics Symposium – ARMA.*

Abstract We present a new fault injection model for induced seismicity in the context of geothermal systems. The characteristic and novelty of our model is that it is both (1) fast and thus allows a probabilistic assessment and (2) purely physic-based in the sense that none unconstrained engineering approach to mimic processes or parameters distributions are used. Our novel approach starts from the most constrained heterogeneous ingredient of the rupture model, that is the geometrical roughness of fault surfaces. Synthetic fractal surfaces mapping real fault geometry are combined with an "instantaneous" slip-weakening model with spatially homogeneous static and dynamic friction coefficients. A rich seismicity's dynamic emerges from the non-trivial interplay between pore pressure diffusion, geometrical heterogeneities of the fault surfaces and stress interactions between the successive rupture events. Solely introducing geometrical heterogeneities as observed for natural faults can explain (1) the occurrence of rupture events at large distance from the injector and (2) the persistence in seismicity post shut-in.

Farkas, M., Hofmann, H., Zimmermann, G., Zang, A. & Yoon, J.S., 2018. Numerical investigation of cyclic hydraulic stimulation and related induced seismicity in Pohang fractured geothermal reservoir, in Proceedings of the 2nd International Discrete Fracture Network Engineering Conference, Seattle, WA, USA, 20–22 June, DFNE 18–781.

Abstract In this study we investigate numerically the flow rate controlled cyclic stimulation experiment performed in August 2017 at the Pohang EGS site using the finite element code FracMan. Per definition, a soft stimulation method aims to increase permeability while reducing the risk of inducing larger seismic events. The numerical code enables studying hydro-mechanical processes and investigating main characteristics of induced seismicity such as spatial evolution of events and their moment magnitude in relation to injected fluid volume in three dimensions. The analysis contributes to understanding the fracturing processes and induced seismicity in naturally compartmentalized fractured reservoir. The code can be also used for predicting the relationship between fluid injection volume and spatial extent of generated or reactivated fractures, i.e. the stimulated reservoir volume. The reservoir model will eventually allow different injection strategies to be investigated to design an optimal stimulation procedure ahead of future field application of soft stimulation. Furthermore, it may also serve as a basis for future numerical investigations.

Fokker, P. A., & Wassing, B. B. (2019). A fast model for THM processes in geothermal applications. In *European Geothermal Congress, EGC* (pp. 11-14).

Abstract We have developed a fast modelling tool, THYMA, for coupled poro-thermo-elastic-plastic behaviour. The tool targets data assimilation and optimization of geothermal operations, like stimulation. A validation with coupled numerical model yielded positive results for elastic responses to the a pressure increase; the implementation and validation of plasticity is in progress.

Fokker, P.A., Singh, A., and Wassing, B.B.T. (2020) A semi-analytic time-resolved poro-elasto-plastic model for wellbore stability and stimulation. Int J Numer Analy Methods Geomech. In press

Abstract Wellbore stability problems and stimulation operations call for models helping in understanding the subsurface behaviour and optimizing engineering performance. We present a fast, iteratively coupled model for the flow and mechanical behaviour that employs a time-sequential approach. Updates of pore pressure are calculated in a timestepping approach and propagated analytically to updates of the mechanical response. This way, the spatial and temporal evolution of pressure and mechanical response around a wellbore can be evaluated. The sequential approach facilitates the incorporation of pressure diffusion and of time-dependent plasticity. Also, it facilitates the implementation of permeability evolving with time, due to plasticity or stimulation. The model has been validated by means of a coupled numerical simulator. Its capabilities are demonstrated with a selection of sensitivity runs for typical parameters. Ongoing investigations target geothermal energy operations through the incorporation of thermo-elastic stresses and more advanced plasticity models.

Grigoli, F., Cesca, S., Priolo, E., Rinaldi, A. P., Clinton, J. F., Stabile, T. A., … Dahm, T. (2017). Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective. Reviews of Geophysics, 55(2), 310–340. https://doi.org/10.1002/2016RG000542

Abstract Due to the deep socio-economic implications, induced seismicity is a timely and increasingly relevant topic of interest for the general public. Cases of induced seismicity have a global distribution and involve a large number of industrial operations, with many documented cases from as far back to the beginning of the 20th century. However, the sparse and fragmented documentation available makes difficult to have a clear picture on our understanding of the physical phenomenon and consequently in our ability to mitigate the risk associated with induced seismicity. This review presents a unified and concise summary of the still open questions related to monitoring, discrimination and management of induced seismicity in the European context and, when possible, provides potential answers. We further discuss selected critical European cases of induced seismicity, which led to the suspension or reduction of the related industrial activities.

Hofmann, H., Zimmermann, G., Zang, A., Aldaz, S., Cesca, S., Heimann, S., Mikulla, S., Milkereit, C., Dahm, T., Huenges, E., Hjörleifsdóttir, V., Snaebjörnsdóttir, S.O., Aradóttir, E.S., Ásgeirsdóttir, R., Ágústsson, K., Magnússon, R., Stefánsson, S.A., Flovenz, Ó., Mignan, A., Broccardo, M., Rinaldi, A.P., Scarabello, L., Karvounis, D., Grigoli, F., Wiemer, S. & Hólmgeirsson, S. (2020) Hydraulic stimulation design for Well RV-43 on Geldinganes, Iceland. Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020.

Abstract The district heating system of the city of Reykjavik is almost exclusively fed by geothermal energy. Due to a growing population and increasing heat demand new heat sources need to be connected to the existing district heating network. One of the remaining potential geothermal systems with suitable conditions can be found on Geldinganes, an uninhabited peninsula within the city limits of Reykjavik. The only production well, RV-43, found the required temperatures, but not the necessary flow rates for economic heat production. Therefore, it is planned to develop this geothermal field by drilling new wells into potentially more permeable zones. Additionally, it is anticipated to hydraulically stimulate the existing well RV-43 in order to improve its hydraulic performance and to add additional production from this well to the heat network. Due to the location of the well within the city limits of Reykjavik, hydraulic stimulation treatments have to be designed to maximize the hydraulic performance increase while minimizing potential environmental risks such as induced seismicity. We provide an overview of the project including the site assessment, conceptual model, planned pre- and post-stimulation measurements, treatment schedule, zonal isolation and multi-stage injection concept, seismic monitoring network and procedures, and seismic risk assessment and seismic risk mitigation procedures, such as the cyclic soft stimulation concept and a site specific traffic light system.

Hofmann, H., Zimmermann, G., Farkas, M., Huenges, E., Zang, A., Leonhardt, M., ... & Fokker, P. (2019). First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea. *Geophysical Journal International*, *217*(2), 926-949.

Abstract Large-magnitude fluid-injection induced seismic events are a potential risk for geothermal energy developments worldwide. One potential risk mitigation measure is the application of cyclic injection schemes. After validation at small (laboratory) and meso (mine) scale, the concept has now been applied for the first time at field scale at the Pohang Enhanced Geothermal System (EGS) site in Korea.
From 7 August until 14 August 2017 a total of 1756 m3 of surface water was injected into Pohang well PX-1 at flow rates between 1 and 10 l s–1, with a maximum wellhead pressure (WHP) of 22.8 MPa, according to a site-specific cyclic soft stimulation schedule and traffic light system. A total of 52 induced microearthquakes were detected in real-time during and shortly after the injection, the largest of*M*w 1.9. After that event a total of 1771m3 of water was produced back from the well over roughly 1 month, during which time no larger-magnitude seismic event was observed. The hydraulic data set exhibits pressure-dependent injectivity increase with fracture opening between 15 and 17 MPa WHP, but no significant permanent transmissivity increase was observed.
The maximum magnitude of the induced seismicity during the stimulation period was below the target threshold of *M*w 2.0 and additional knowledge about the stimulated reservoir was gained. Additionally, the technical feasibility of cyclic injection at field scale was evaluated. The major factors that limited the maximum earthquake magnitude are believed to be: limiting the injected net fluid volume, flowback after the occurrence of the largest induced seismic event, using a cyclic injection scheme, the application of a traffic light system, and including *a priori* information from previous investigations and operations in the treatment design.

Hofmann, H., Zimmermann, G., Zang, A. & Min, K.-B. (2018) Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments. *Geothermal Energy*, 6, 27.

Abstract Hydraulic stimulation treatments are standard techniques to access geologic resources which cannot economically be exploited with conventional methods. Fluid injection into unproductive formations may increase their permeability by forming new fractures and activating existing ones. A major risk of this process is a possible occurrence of seismic events that can potentially be felt on the surface or even cause minor damage. In this paper, an advanced fluid injection scheme is proposed that aims to mitigate these unwanted events and to improve the permeability enhancement process. Amongst other procedures, it involves different types of cyclic injection and a traffic light system specifically designed for cyclic injection schemes. The concept is applied to develop a stimulation design for the Pohang enhanced geothermal system site in Korea, where it was first deployed in the field in August 2017.

Karvounis and Wiemer, (2020) Forecasting Induced Seismicity and Maximizing Production of Electricity in EGS. Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020.

Abstract Enhanced Geothermal Systems (EGS) has been for decades considered to be one of the best candidate technologies for exploiting the abundant geothermal energy stored in non-volcanic regions and their further development is now eminently needed for decarbonizing our society. Induced seismicity due to the stimulation of EGS reservoirs has been a major setback for the development of the technology since investors need not only to consider the risk of drilling an underperforming well, but also the seismic hazard and its social aspects. The governmentality of EGS is further restricted by the limited experience from successful EGS stimulations, the large number of possible scenarios that need to be considered, and by the complexity of the analytical models that best describe the physical processes during stimulation. Here, a Discrete Fracture Hybrid Model (DFHM) is employed for numerical studies, which DFHM combines deterministic numerical modeling of flow inside discrete fractures with stochastic modeling of seismicity. Given a stimulation strategy for the wells of an EGS, the DFHM returns in time for real-time applications both forecasts of induced seismicity that are useful for Probabilistic Seismic Hazard Assessments (PSHA) and forecasts of the maximum expected electrical power generation that is useful for Probabilistic Reservoir Performance Assessments (PRPA). Inference, prediction, probabilistic optimization, and uncertainty quantification can be performed with the DFHM for several scenarios related to induced seismicity in unconventional fractured reservoirs, for which scenarios conventional PSHA approaches fail due to their simplifications. The concept of multi-staged soft stimulation is tested with the DFHM, where both PSHA and PRPA are performed and compared with past single-staged strategies.

Mignan, A., Broccardo, M., Wiemer, S., & Giardini, D. (2017). Induced seismicity closed-form traffic light system for actuarial decision-making during deep fluid injections. Scientific Reports, 7(1), 1–10. https://doi.org/10.1038/s41598-017-13585-9

Abstract The rise in the frequency of anthropogenic earthquakes due to deep fluid injections is posing serious economic, societal, and legal challenges to many geo-energy and waste-disposal projects. Existing tools to assess such problems are still inherently heuristic and mostly based on expert elicitation (so-called clinical judgment). We propose, as a complementary approach, an adaptive traffic light system (ATLS) that is function of a statistical model of induced seismicity. It offers an actuarial judgement of the risk, which is based on a mapping between earthquake magnitude and risk. Using data from six underground reservoir stimulation experiments, mostly from Enhanced Geothermal Systems, we illustrate how such a data-driven adaptive forecasting system could guarantee a risk-based safety target. The proposed model, which includes a linear relationship between seismicity rate and flow rate, as well as a normal diffusion process for post-injection, is first confirmed to be representative of the data. Being integrable, the model yields a closed-form ATLS solution that is both transparent and robust. Although simulations verify that the safety target is consistently ensured when the ATLS is applied, the model from which simulations are generated is validated on a limited dataset, hence still requiring further tests in additional fluid injection environments.

Salina Borello, E., Fokker, P. A., Viberti, D., Verga, F., Hofmann, H., Meier, P., ... & Zimmermann, G. (2019). Harmonic Pulse Testing for Well Monitoring: application to a fractured geothermal reservoir. *Water Resources Research*.

Abstract Harmonic Pulse Testing (HPT) has been developed as a type of well testing applicable during ongoing field operations because a pulsed signal is superimposed on background pressure trend. Its purpose is to determine well and formation parameters such as wellbore storage, skin, permeability, and boundaries within the investigated volume. Compared to conventional well testing, HPT requires more time to investigate the same reservoir volume. The advantage is that it does not require the interruption of well and reservoir injection/production before and/or during the test because it allows the extraction of an interpretable periodic signal from measured pressure potentially affected by interference. This makes it an ideal monitoring tool. Interpretation is streamlined through diagnostic plots mimicking conventional well test interpretation methods. To this end, analytical solutions in the frequency domain are available. The methodology was applied to monitor stimulation operations performed at an Enhanced Geothermal System site in Pohang, Korea. The activities were divided into two steps: first, a preliminary sequence of tests, injection/fall-off, and two HPTs, characterized by low injection rates and dedicated to estimate permeability prior to stimulation operations, and then stimulation sequence characterized by a higher injection rate. During the stimulation operations other HPT were performed to monitor formation properties behavior. The interpretation of HPT data through the derivative approach implemented in the frequency domain provided reliable results in agreement with the injection test. Moreover, it provided an estimation of hydraulic properties without cessation of stimulation operations, thus confirming the effectiveness of HPT application for monitoring purposes.

van Wees, J. D., Kahrobaei, S., Osinga, S., Wassing, B., Buijze, L., Candela, T., Fokker, P., ter Heege, J., Vrijlandt, M. (2019b). 3D models for stress changes and seismic hazard assessment in geothermal doublet systems in the Netherlands. Proceedings World Geothermal Congress 2020 - Reykjavik, Iceland, April 26 – May 2, 2020.

Abstract The role of geothermal energy production as a source of a sustainable energy for district heating in the Netherlands is expected to grow, from 20 geothermal doublets currently in operation to around 175 doublets in 2030 . Current geothermal doublets and planned doublets produce from porous sandstone aquifers of Tertiary, Cretaceous/Jurassic, Permian (Rotliegend), and Triassic age and fractured carbonate rocks of Dinantian age. Production temperatures of the conventional doublets are generally between 65 – 100 °C, and fluids are re-injected at temperatures between 20 - 45°C. Cooling of reservoir rocks and surrounding rock mass can lead to significant thermal stresses, which, superimposed on the pressure induced stress changes, may affect fault stability and may lead to an increased seismicity hazard. In particular, doublets drilled in competent rock types and marked by large temperature contrasts are prone to a high likelihood for the build-up of significant thermal stresses over time (>>1MPa). For safe and effective operations, it is important to assess the long-term combined effect of pore pressure and temperature changes in geothermal operations on fault stability and associated seismicity, taking into account (1) operational parameters such as injection temperatures, pressures, flow rates volumes and (2) in-situ geological, geohydrological and geomechanical factors.
We developed a 3D workflow, capable of assessing both pressure and thermal evolution and its effects on stress changes on faults, which can be used to evaluate seismic hazard. The workflow is designed for complex faulted reservoirs, taking into account the aforementioned operational and in-situ factors. The workflow easily quantifies the effect of long-term cooling during geothermal operations on fault stresses, which can be used for fault reactivation potential and seismic hazard, for typical conventional geothermal doublets. In this paper the workflow is demonstrated for relatively simple reservoir geometries in the most common geological settings in The Netherlands, i.e. homogeneous porous sandstone reservoir (representative of the Cretaceous/Jurassic, Rotliegend and Triassic reservoirs in the south-western and northern part of The Netherlands).
Results for homogeneous and faulted porous sandstone reservoirs indicated that geothermal doublet operations, can cause thermal stressing causes a significant increase of Coulomb stresses and can have a destabilizing effect on fault stability within the vicinity of the geothermal doublets. Increased pore pressures can cause additional positive Coulomb stressing of the faults; however, the effect of pore pressure is limited in areal extent and relatively small compared to the effect of thermal stresses, except in the first years of operation.

Wassing et al., (2019). Modelling the effect of hydraulic stimulation strategies on fault reactivation and induced seismicity. In European Geothermal Congress, EGC.

Abstract Hydraulic stimulation is frequently used to enhance the permeability of natural fracture networks in deep low-permeability rocks. The downside of hydraulic stimulation of pre-existing fractures is that it may trigger felt induced seismicity through reactivation. For a successful development of enhanced geothermal systems, it is crucial to stimulate rocks to enhance flow rate, whilst keeping magnitudes of induced earthquakes at acceptable levels by means of so-called ‘soft’ hydraulic stimulation.

Here we use a 3D coupled Thermal-Hydraulic-Mechanical model in Tough2-FLAC3D to simulate the effect of different stimulation strategies on the characteristics of fault reactivation and induced seismicity. Using the Tough2-FLAC3D simulator, we take into account the full coupling between the hydraulic and mechanical processes affecting flow through the reservoir and the mechanical response of the fault system. We model fluid injection into a single well, at close distance to a single fault, bounded by a fault damage zone and embedded in a fractured rock matrix. For different injection scenarios, we analyze the impact on fault stress changes, fault stressing rates and associated seismicity. We discuss the effect of the different stimulation strategies on the evolution of induced seismicity both

during and after hydraulic stimulation. We also discuss the effect of fault transmissibility on induced seismicity and effectiveness of the stimulation strategies.

Wassing et al, in preparation (2020) FLAC-TOUGH on Pohang

Welter et al, 2019. Key Performance Indicators with the use of Monte Carlo simulation

Abstract The EU H2020 project DESTRESS shall demonstrate the application of stimulation techniques in different plays. The overall goal is an improvement of hydraulic reservoir parameters with minimal impact on environment and residents. Besides the applied research the investigation of risk factors as well as the economic effect of soft stimulation is a part of the DESTRESS project. The report at hand combines the topics uncertainty/risk factors and economic evaluation. The integration of uncertainty in general and uncertainty of risk factors in particular, is a further development step in the techno-economic evaluation of geothermal power.

The integration of uncertainty into techno-economic modelling is not completely new in industries looking for underground resources. One of the synergies coming from oil and gas business is the approach of decision analysis that integrates techno-economic evaluation with uncertainty into decision making. Decision analysis is presented in detail in this report. The approach shall improve the quality of decisions in project development and operation and thereby enhance the success of geothermal projects. The uncertainty caused by risk factors is a major topic of this report. The quantification of risk factors presented in this study, enables the integration of uncertainty into techno-economic modelling. Identification and quantification of risk factors are important elements of risk management. For project developers/operators the risk mitigation, as part of risk management, is even more interesting. Therefore, mitigation measures and the evaluation of mitigation measures are also analyzed. The main subject of the study at hand is a techno-economic model of geothermal heat and power plants which is developed to determine the impact of technical and economic risk factors on levelized cost of heat and electricity. To investigate those correlations, the Monte Carlo method is used. Altogether the model consists of three main parts: the reservoir, the thermal fluid cycle and the heat or power plant, respectively. The power plant is implemented as an Organic Rankine Cycle. Pure power or heat generation as well as combined heat and power in parallel and serial setup are considered. Furthermore, both continuous operation and heat-driven operation dependent on a predefined heat load are considered. The model is explained in detail and applied to the three selected demonstration sites. The aim is to demonstrate the "integrated geothermal energy model" (IGEM) and evaluate soft stimulation measures including uncertainty caused by risk factors. On the example of the Soultz-sous-Forêts site, the possibilities and first results of power plant optimization with the Monte-Carlo approach are demonstrated. In addition, the technical effects of the implemented risk factors are shown. The implemented risk factors also affect model parameters on an economic level. These effects are demonstrated on the example of the heat plant in Mezöberény (Hungary). The Mezöberény site is also used to show the enhancement of hydraulic parameters through a stimulation and their effect on selected key performance indicators (KPI). The report is concluded with a comparison of pure electricity provision and combined heat and power (CHP) on the example of a fictitious site in the Upper Rhine Graben (Germany). Based on the frame conditions of this site, a comparison is drawn between geothermal heat supply and other renewable and conventional energy sources capable of large-scale heat provision.

Imprint

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