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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691728

The First Two Hydraulic Stimulations in the Pohang Geothermal Development Site, South Korea: Field Observations and Numerical Modeling

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1. Introduction

Five hydraulic stimulations were conducted at the Pohang EGS project site in Pohang, a city in southeastern Korea in 2016-2017. Three stimulations were in a vertical well, PX-2, drilled to 4.3 km, and two in an inclined well, PX-1, drilled to 4.1 km depths. This poster presents key observations, analyses, and numerical modeling of the first and second stimulations at the Pohang EGS site as a summary of Park et al. (2020) and Yoo et al. (2021). We present hydraulic and seismic data obtained during hydraulic stimulations and analyses of transmissivity and fracture aperture change, injectivity evaluation, and key mechanisms of hydraulic stimulations. We also intended to improve the understanding on the hydraulic stimulations in the project through hydro-mechanical coupled numerical analyses for the early days of the stimulations.

2. Observed results

2.1 The first hydraulic stimulation at PX-2

- Maximum flow rate: 46.8 L/s
- Maximum wellhead pressure: 89.2 MPa.
- The total injected volume:1970 m^3
- The largest seismic event: M_L 1.7.

Wellhead pressure peaks at 64-67 MPa and following pressure declines on the first day of the first stimulation indicate sudden opening of flow channel by stimulation mechanisms at high pressure.

While drilling, considerable amount of high-density drilling mud was lost in 3.8–4.3 km depths, followed by a use of lost circulation materials (LCM). Hydraulic damage of PX-2 was possibly led.

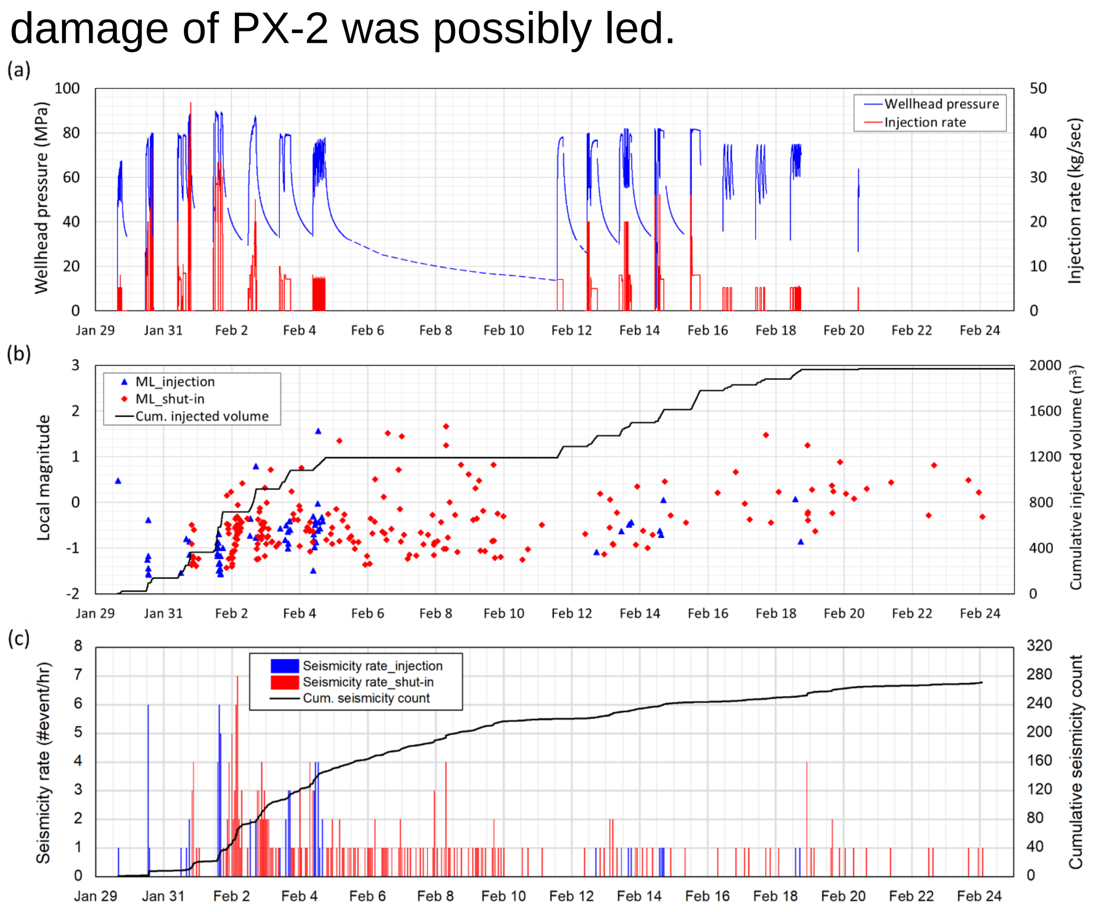

Figure 1. Overall data of the first stimulation conducted in PX-2 (Park et al., 2020).

2.2 The second hydraulic stimulation at PX-1

- Maximum flow rate: 18.0 L/s
- Maximum wellhead pressure: 27.7 MPa
- The total injected volume: 3907 m^3
- The largest seismic event: M_L 2.2.

Wellhead pressure peaks at 15-17 MPa, considerably lower than PX-2, can be interpreted as clear signs of flow channels opening with better hydraulic performance and distinct stimulation mechanism compared to PX-2.

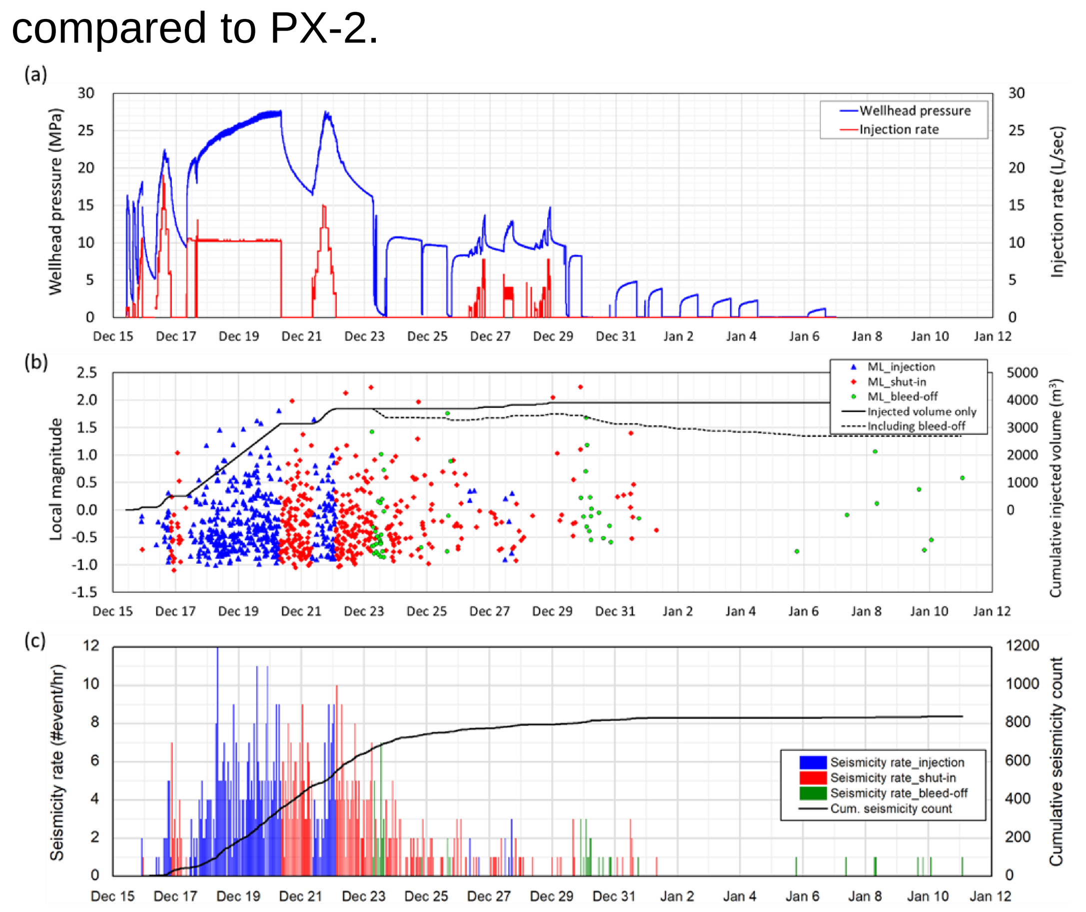

Figure 2. Overall data of the second stimulation conducted in PX-1 (Park et al., 2020).

2.3 Seismicity during the two stimulations

Increases of seismicity magnitude and rate were observed after shut-ins in both the first and second stimulations. The largest event in each stimulation also occurred during the shut-in periods.

3. Data analyses

3.1 Evaluations of hydraulic properties

The two stimulations showed distinctly different hydraulic characteristics along with pressure changes.

- In PX-1, the transmissivity and equivalent aperture of the flow channel showed weaker correlations with the pressure level. The transmissivity increased approximately 6.4 times during the second stimulation.
- In PX-2, the opening of the surrounding rock showed a strong correlation with the pressure level. The rock was initially very tight but drastically opened at high pressure, following a non-linear and reversible trend.
- The wellhead injectivity showed a limited increase in PX-1 and a slight decrease in PX-2. The overall range of wellhead injectivity in PX-1 was approximately 3.6 times higher than PX-2.

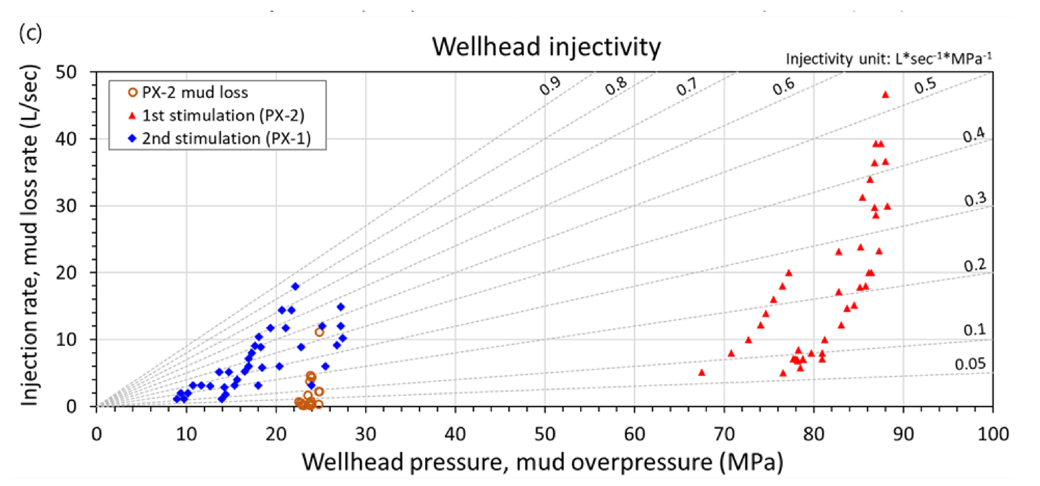

Figure 3. Wellhead injectivity during the first and second hydraulic stimulations (Park et al., 2020).

3.2 Stimulation mechanisms

In PX-2, it can be interpreted as prevailing hydraulic jacking, or a transition from hydraulic fracture extension to dominant hydraulic jacking based on:

- the analogies with the theoretical models and field observations in earlier studies;
- the fact that no clear evidence of major contribution by hydraulic shear-dilation to the transmissivity near the wellbore;
- the assumption of severe well damage by heavy mud, LCM, or improper cementing.

In PX-1, it can be interpreted as a combination of shear dilation and hydraulic jacking because

- the increase in equivalent aperture included both permanent and reversible portions, and occurred gradually with pressure increase, at the pressure range much lower than PX-2;
- the openhole section was 2.3 times longer than PX-2 and the uses of heavy mud or LCM were constrained. Thus it was advantageous to maintain hydraulic connections with undamaged natural fractures.

3.3 Relation between seismic magnitude and injected volume

All the induced seismic events during the first two stimulations stayed below the maximum magnitude and maximum arrested rupture magnitude suggested as theoretical models in the previous studies.

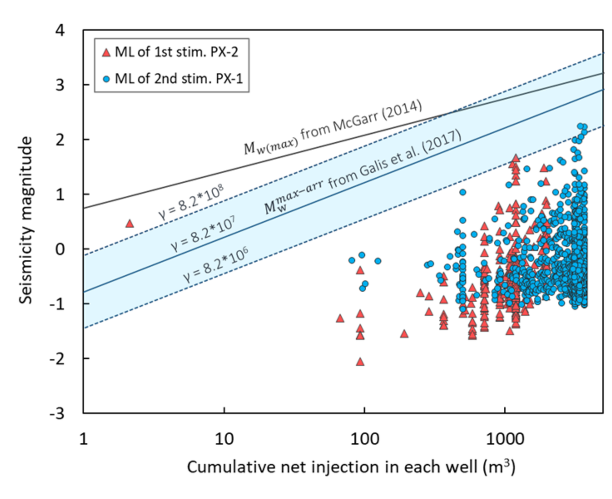

Figure 4. Local magnitude-volume relations plotted with the maximum moment magnitude by McGarr (2014) and the maximum arrested rupture magnitude by Galis et al. (2017) (Park et al., 2020).

4. Numerical modeling

4.1 Model setup

Two models were established separately for each well with different fracture orientations under the same in-situ stress model by using the TOUGH-FLAC simulator. The properties for the fracture zone were obtained from calibrations through a history matching of wellhead pressure. A hydraulic jacking mechanism was applied to the PX-2 model by using an exponential hydraulic aperture function of effective normal stress. In the PX-1 model, a combination of shear dilation and jacking was implemented with frictional plastic strain-softening.

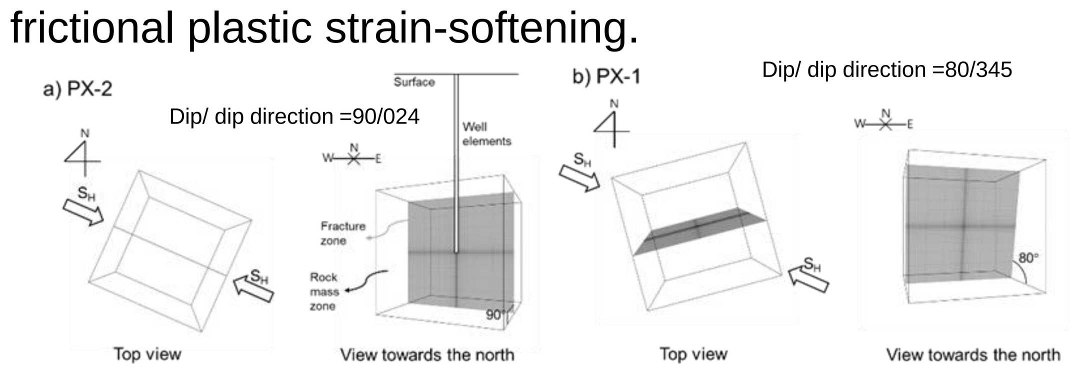

Figure 5. Model configuration of (a) PX-2 and (b) PX-1; top view and view towards the north (Yoo et al., 2021).

4.2 Hydro-mechanical simulation results

- The PX-2 model captured the distinct pressure response around 67 MPa in Stages I and II
- The PX-1 model achieved a remarkable similarity to the observed pressure on the first day with a reproduction of the breakdown pressure at 16 MPa in Stage I
- The better fit of C2, which had a half hydraulic aperture function 75 m away from PX-1, at the later stage strongly suggests a possible presence of zones with less permeability or even an impermeable barrier away from the PX-1 well.
- Due to local stress changes by the poroelastic effect, the onset of shear slip was observed at a higher wellhead pressure than predicted by a simple slip potential analysis.

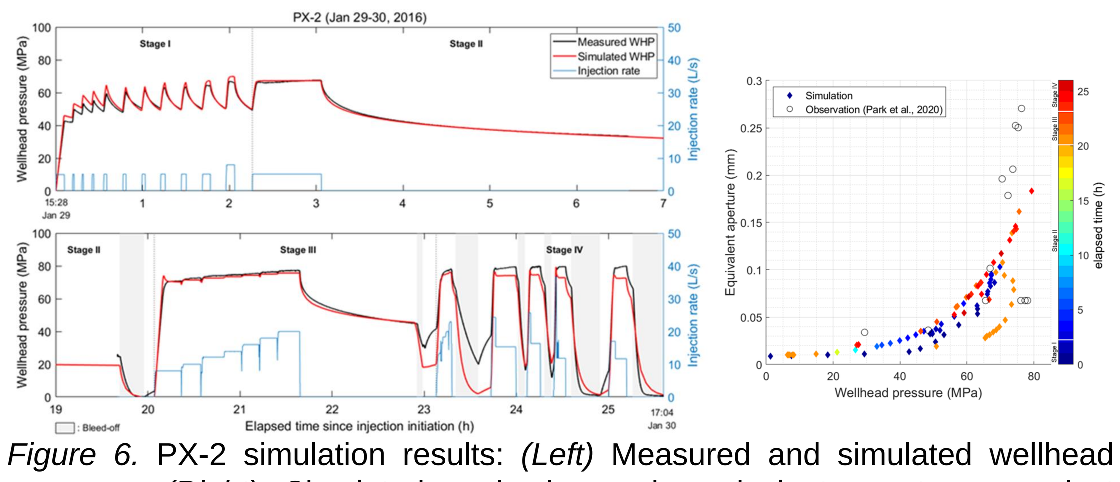

Figure 6. PX-2 simulation results: *(Left)* Measured and simulated wellhead pressure; *(Right)* Simulated and observed equivalent apertures against wellhead pressure (Yoo et al., 2021).

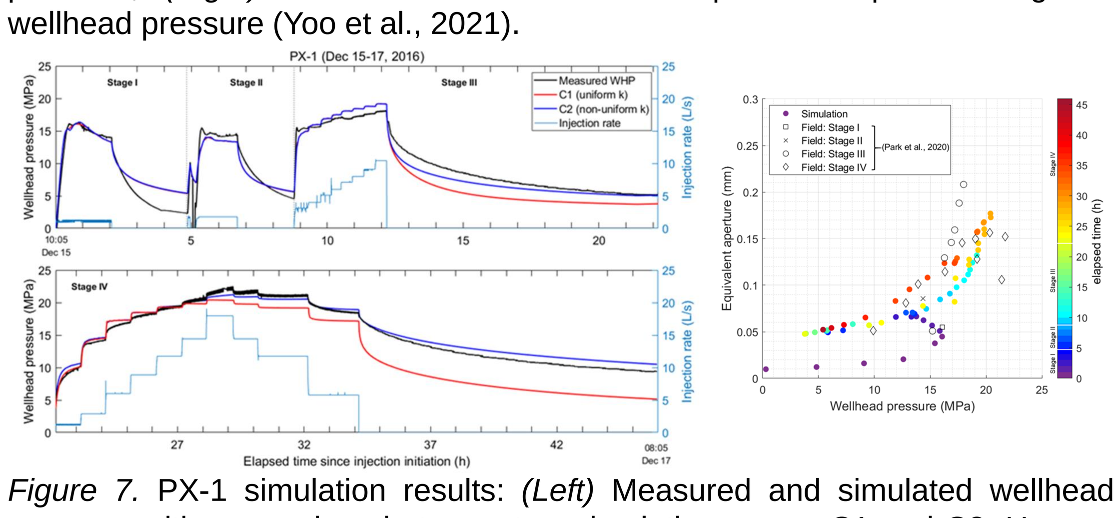

Figure 7. PX-1 simulation results: *(Left)* Measured and simulated wellhead pressure with comparison between two simulation cases, C1 and C2. Unseen C1 (red) pressure curves in some periods were because of the overlap with C2 (blue); *(Right)* Simulated and observed equivalent apertures against wellhead pressure (Yoo et al., 2021).

5. Conclusion

The two nearby wells at the Pohang EGS site showed distinctly different hydromechanical characteristics and stimulation mechanisms. The early pressure histories in the two wells were successfully modeled by the coupled hydro-mechanical processes.

Acknowledgements

The preparation of this poster presentation was supported by a grant from the Human Resources Development program (No. 20204010600250) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), funded by the Ministry of Trade, Industry, and Energy of the Korean Government.

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