Induced Seismicity Protocol for the First Enhanced Geothermal Systems Project in Pohang, Korea

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Introduction

Induced microseismicity has been regarded as a key component for the first EGS project initiated in Pohang, Korea which started in 2010. A regional case study of geothermal energy development in South Korea focusing on the comprehensive protocol addressing induced microseismicity is presented in this study. The protocol largely follows the seven steps suggested by the Department of Energy in United States with site specific adjustment and improvement as necessary. Site selection procedure, outreach program, establishment of local seismic network, and methodology in establishing traffic light system are introduced together with analysis of induced microseismicity from the first hydraulic stimulation campaign. The traffic light system was applied to the first hydraulic stimulation operated in January and February of 2016, and calibrated with induced microseismicity

Pohang EGS Project (Dec, 2010 ~)

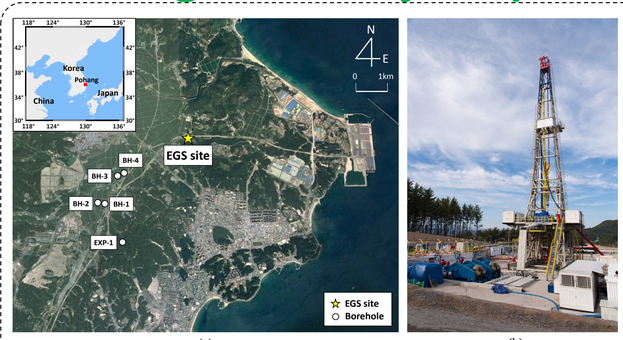


Fig. 1. (a) A map showing the location of Pohang EGS site and five boreholes (b) a picture of Pohang EGS site.

- **Location**: Pohang, South Korea (Fig. 1).
- **Boreholes**
  PX-1 (4.2 km), PX-2 (4.3 km) at EGS site
  BH-1, BH-2, BH-3, BH-4, EXP-1 (1 ~ 2 km)
- **Geothermal gradient**: 41 °C/km (103.8 °C at 2,170 m depth of PX-1 borehole) (Yoon et al., 2015)
- **1st Hydraulic stimulation** (PX-2, Jan ~ Feb, 2016)
  Total injected volume: 1,970 m^3
  Total number of induced seismicity: 362
  Maximum magnitude: M_W 1.4

* The second hydraulic stimulation was conducted at the end of 2016 at PX-1 borehole, but this study focuses on the first hydraulic stimulation.

U.S. DOE Induced Seismicity Protocol

The US DOE protocol intends to facilitate the successful development of EGS projects by assuring policymakers and the public of a safe and cost effective geothermal development.

Table 1. Seven steps suggested by U.S. DOE for addressing induced seismicity (Majer et al., 2012).

Steps	Implementations
Step 1	Perform preliminary screening evaluation
Step 2	Implement an Outreach and Communication program
Step 3	Review and select criteria for ground vibration and noise
Step 4	Establish local seismic monitoring
Step 5	Quantity the hazard from natural and induced seismic events
Step 6	Characterize the risk of induced seismic events
Step 7	Develop risk-based mitigation plan

Induced Seismicity Protocol for the Pohang EGS project

Step 1: Preliminary screening evaluation

Five candidate sites and site selection based on five categories

1) type of geothermal energy **2)** the quality of existing geological data **3)** geothermal gradient **4)** regional infrastructure **5)** allowed time for site investigation.

Pohang was chosen as the most suitable site for the first EGS project mainly because of confirmed higher geothermal gradients with existing deep boreholes and easier access to the city.

Step 2: Outreach and communications program

The inauguration ceremony in August 2012 was a platform for communication with local governments and residents. As of September 2016, the total number of visitors was 740 from 173 organizations (Fig. 2).

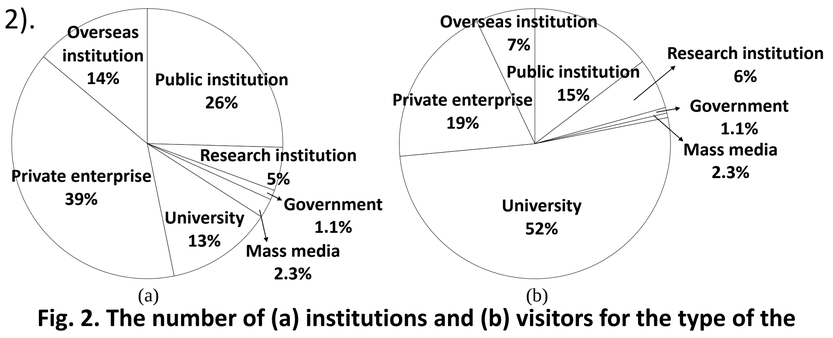


Fig. 2. The number of (a) institutions and (b) visitors for the type of the affiliations from project initiation to September 6th, 2016.

Step 3: Review and selection of criteria for ground vibration

Regulations and standards for ground vibration in South Korea were reviewed, and a new standard covering the Pohang EGS project was suggested by considering **domestic criteria** and **human responses** to ground vibration.

Table 2. Criteria on ground vibration for different types of buildings (MOCT, 2002)

Type of buildings	Threshold of ground velocity (cm/s)
Cultural heritage	0.2
Structures with masonry wall and wood ceiling	1
Structures with underground foundations and concrete slabs	2
Low storied structures with steel concrete frameworks and slabs	3
High storied structures with steel concrete frameworks and slabs	5

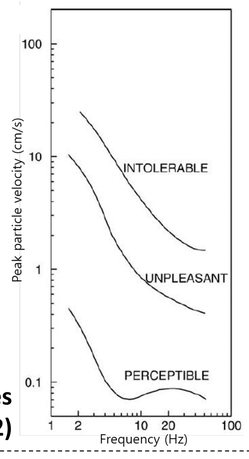


Fig. 3. Human response to vibration as frequency of vibration changes (USACE, 1972)

Step 4: Establishment of local seismic monitoring network

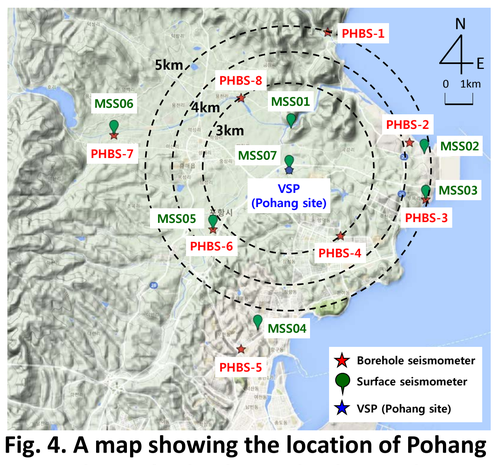


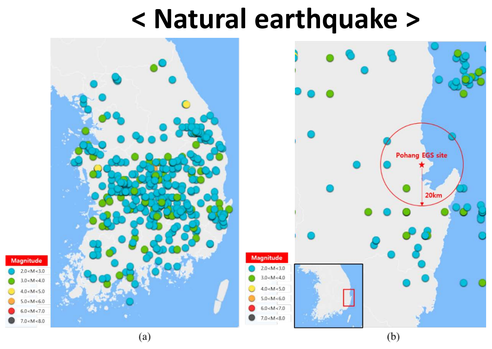
Fig. 4. A map showing the location of Pohang EGS site and seismic monitoring stations.

DOE's suggestion (Majer et al., 2012)
- At least 8 three-component accelerometers.
- More than 5 sensors should be able to locate sufficient seismic events reliably.
- Events smaller than magnitude 1.0 should be able to be detected.

Pohang EGS project (Fig. 4)
- 8 Borehole seismometer: 120 ~ 130 m depth
- Vertical Seismic Profile (3 sensors): 10m interval from 1,360m depth of PX-1 hole
- Seven temporary surface seismometers
- High-speed internet network with a sampling frequency of as high as 1,000 Hz in real time.

Step 5: Quantification of hazards from natural and induced seismic events

< Natural earthquake >



0.41 times/km2 **0.24 times/km2**

Fig. 5. Location and magnitude of earthquake events larger than 2.0 in (a) South Korea and (b) Pohang region for the past 39 years.

< Microseismicity near Pohang site >

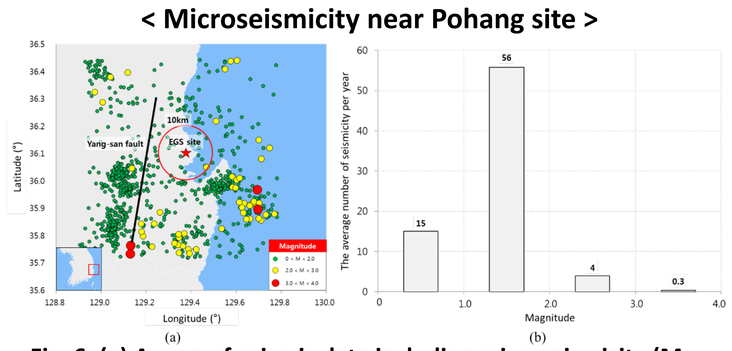


Fig. 6. (a) A map of seismic data including microseismicity (M_L > 0) near Pohang area from 1998 to 2001 (b) Bar graphs indicating the average number of seismic events per year within 50 km radius by the magnitude.

Step 6: Characterization of the risk of induced seismic events

An estimated equation for blasting vibration was converted to an equation relating peak ground velocity (PGV) to magnitude

< An estimated equation for blasting vibration >

$$Log(V) = Log(K) + nLog(SD), (SD = R/W^b)$$

V: Peak ground velocity [cm/s] R: distance [m]
W: amount of explosives [kg] b: 1/2 or 1/3
K: Site-specific constant n: attenuation index
SD: Scaled distance [m/kg$^{1/2 \text{ or } 1/3}$]

< Seismic energy - M_L equation >

$Log(E) = 3.6 + 2M_L$ (Tobyáš and Mittag, 1991)

< Radiated energy per 1kg of explosives >

$E = 3.8 \times 10^6$ J/kg

< Determination of site-specific coefficients (K, n) >

30 natural earthquakes near Pohang site

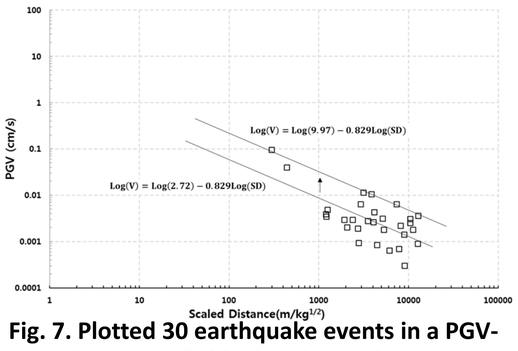


Fig. 7. Plotted 30 earthquake events in a PGV-Scaled Distance field when b equals to 1/2.

$$Log(V) = Log(9.97) - 0.829Log(SD)$$

$$SD = R/\left(\frac{10^{3.6+2M_L}}{3.8 \times 10^6}\right)^{1/2}$$

Step 7: Development of mitigation plan

PGV-M_L equation + domestic criteria and human response to ground vibration

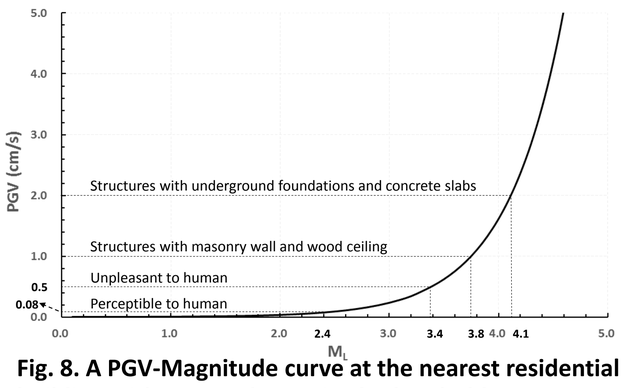
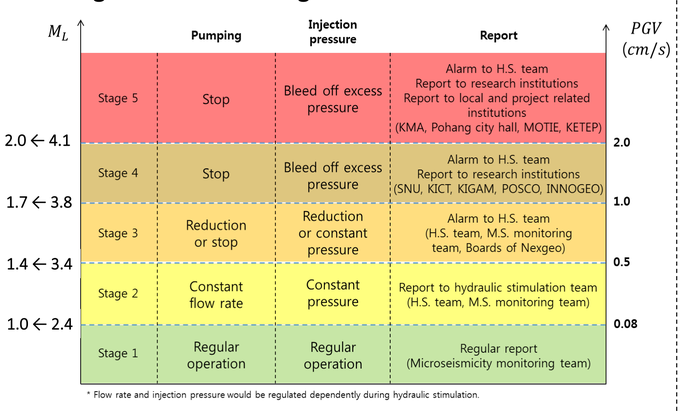


Fig. 8. A PGV-Magnitude curve at the nearest residential building with PGV and magnitude thresholds.



* Flow rate and injection pressure would be regulated dependently during hydraulic stimulation.

Fig. 9. The traffic light system for Pohang EGS project.

- Close reference to Basel's traffic light system
- Safety factor: 1.4 ~ 2.1

Step 8: Application and Calibration

Table 3. Data of induced seismic events detected by surface seismometers during the first hydraulic stimulation.

Date and Time (UTC)	M_w	PGV (10^{-3}cm/s)	Sensor
20160204 03:55:37	1.1	4.45	MSS01
20160204 19:09:41	1.4	6.46	MSS01
		10.5	MSS01
20160206 05:11:15	1.3	5.05	MSS05
		2.92	MSS06
20160206 12:36:37	0.5	0.478	MSS01
20160206 15:01:15	1.2	5.80	MSS01
20160207 22:03:49	1.4	21.8	MSS01
20160207 22:03:52	1.3	12.4	MSS01
20160207 22:04:41	0.8	2.10	MSS01
20160208 08:41:49	0.6	1.21	MSS01
20160208 14:14:37	0.7	0.950	MSS01
20160209 07:33:57	0.5	0.728	MSS01
20160216 10:35:05	0.5	0.687	MSS01
20160217 07:43:44	1.0	4.43	MSS01
20160218 13:08:12	1.1	7.61	MSS01
20160219 12:03:28	0.9	6.55	MSS01

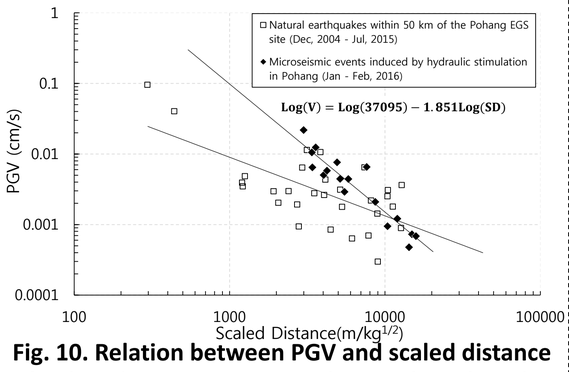


Fig. 10. Relation between PGV and scaled distance of induced seismic events and natural earthquakes

- The obtained seismic data falls roughly within the suggested empirical equation
- But the induced seismic data shows a much steeper trend than natural earthquakes.

Acknowledgement & References

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