QUANTITATIVE ANALYSIS OF EARTHQUAKE ENERGY INDUCED BY WATER INJECTION FOR HOT DRY ROCK POWER GENERATION

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ABSTRACT

High water utilization efficiency is important as well as high generation efficiency when implementing Hot Dry Rock power generation (HDR). In addition, hydraulic fracturing performed to create reservoirs requires suppressing induced earthquakes. However, the relation between conditions of hydraulic fracturing and the magnitude of the induced earthquake has not been clarified. We showed the relationship between the injection energy of hydraulic fracturing and the induced earthquake energy.

We selected 6 sites with injection point depth of 1000 to 5000 m; Hijiori, Ogachi, Newberry, Soultz, Cooper Basin, Basel. The injection energy was calculated from wellhead pressure, flow rate and operating time of injection water and the induced earthquake energy was calculated using the Gutenberg-Richter equation.

As a result, the ratios of the total energy of induced earthquakes to the injection energy at Hijiori and Ogachi sites were as low as 0.1% or less, but the ratios at Cooper Basin and Basel sites were as high as about 5%. The ratios at Newberry and Soultz sites were in between. The ratio of the induced earthquake energy greatly varies depending on the difference in underground structure.

The evaluation method from the viewpoint of the injection energy and the induced earthquake energy is useful for selection of HDR site and planning of effective operation conditions.

1. INTRODUCTION

For implementation of HDR, it is necessary to create an artificial reservoir in the underground hot rock layer by hydraulic fracturing. When hydraulic fracturing is carried out, with the production of a reservoir having a proper size and permeability, it is necessary to reduce the earthquake energy. Quantitative relationships between hydraulic fracturing energy and induced earthquakes energy in the demonstration tests of HDR conducted in the world have not been clarified except a few articles (Kaieda et al., 2010),(Boroumand and Eaton, 2012).

Induced earthquakes are often discussed in relation to seismic moment, but we focused on energy in this papers. The injection energy was calculated by the product of wellhead pressure, flow rate and operating time, and the energy of induced earthquakes was calculated by Gutenberg-Richter equation using published earthquake magnitude.

The relation of the induced earthquake energy to the injection energy was clarified for 6 sites with injection point depth of 1000 to 5000 m. Six experimental sites are located in Hijiori, Ogachi, Newberry, Soultz, Cooper Basin and Basel.

2. CALCULATION OF INJECTION ENERGY AND INDUCED ERATHQUAKE ENERGY

2.1 Total water injection energy

High pressure water is injected through the borehole into the hot rock mass by pumps in hydraulic fracturing. Injection energy Ei (J) can be expressed by the product of wellhead pressure P (Pa), water flow rate F (m3/s), and injection time t (s) as shown in equation (1).

$$Ei = P \times F \times t \qquad (1)$$

As an example, we show the hydraulic fracturing data conducted in 1991 in the demonstration test of Ogachi site (Kaieda et al., 2010). Using the data of injection water pressure, flow rate and time of hydraulic fracturing for 12 days from 8/26 to 9/6 shown in Figure 1, the injection energy was calculated to be 189 GJ.

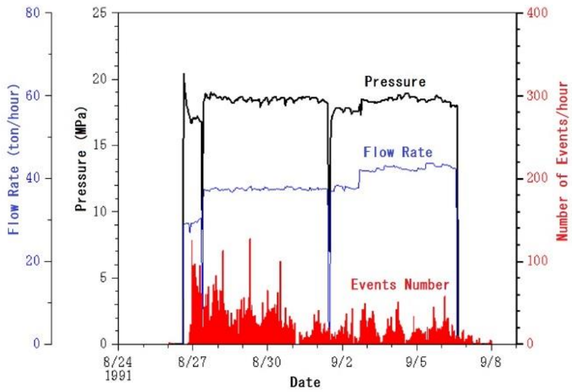


Figure 1: Hydraulic fracturing parameters in Ogachi (Kaieda et al., 2010)

Similarly, the other 5 sites data (Kaieda et al., 2010), (Petty et al., 2013), (Dorbath et al., 2009), (Häring et al., 2008) were used to calculate the water injection energies Ei. The results are shown in Table 1.

Table 1: Injection energy

Site	Water Suppling Period(days)	Ei (GJ)
Hijiori	1	46.6
Ogachi	12	189
Newberry	53	347
Soultz	7	300

Cooper Basin	11	879
Basel	7	288

2.2 Total induced earthquake energy

2.2.1 Hijiori (Japan)

The number of located induced earthquakes observed in hydraulic fracturing at Hijiori site in 1992 was 107. The maximum magnitude of the induced earthquake was 0.3, and the magnitude of the other induced earthquakes was less than -1.0 (Kaieda et al., 2010). Since the earthquake energy with magnitude of -1.0 or less is negligibly small, the earthquake energy with magnitude of 0.3 calculated by the Gutenberg-Richter formula (Gutenberg and Richter, 1956) expressed in equation (2) was taken as the total earthquake energy. The total induced earthquake energy was calculated to be 0.0002 GJ.

$$E = 10^{(1.5M+4.8)} \quad (2)$$

Here, E(J) is the earthquake energy, and M is the seismic magnitude.

2.2.2 Ogachi (Japan)

The number of located induced earthquakes observed in hydraulic fracturing at Ogachi site in 1991 was 1,553. The maximum magnitude of the induced earthquake was 2.0, and the magnitude of the other induced earthquakes was less than -1.0 (Kaieda et al., 2010). Earthquake energy with a magnitude of 2.0 calculated by the Gutenberg-Richter equation shown in equation (2) was taken as the total induced earthquake energy. The total induced earthquake energy was calculated to be 0.06 GJ.

2.2.3 Newberry (Oregon, USA)

The number of located earthquakes observed by hydraulic fracturing at Newberry site in 2012 was 385, and maximum magnitude was 2.6 (Geothermal Data Repository). The sum of all induced earthquake energy was calculated by equation (2), and the total induced earthquake energy was calculated to be 4.1 GJ.

2.2.4 Soultz (France)

The number of located earthquakes observed by hydraulic fracturing at Soultz in 2000 was 14,000, and maximum magnitude was 2.6 (Dorbath et al., 2009). Induced earthquake energy of 220 earthquakes with magnitude of 1.5 or more among them was calculated to be 6.8 GJ. The earthquake energy with magnitude of 1.5 or less is small compared to the maximum magnitude of 2.6, therefore 6.8GJ is used as the total induced earthquake energy here.

2.2.5 Cooper Basin (Australia)

The number of located earthquakes observed by hydraulic fracturing at Cooper Basin site in 2003 was 5,029, and maximum magnitude was 3.7 (Kaieda et al., 2010). The magnitude of 11 earthquakes with magnitude of 2.5 or more are disclosed (Geoscience Australia). The total induced earthquake energy of these 11 earthquakes was calculated to be 56 GJ. Considering that the maximum magnitude is as high as 3.7, the number of 11 induced earthquakes may be too small to calculate the total induced earthquake energy.

2.2.6 Basel (Swiss)

The number of located earthquakes observed by hydraulic fracturing at Basel site in 2006 was 3,500, and the maximum magnitude was 3.4 (Häring et al., 2008). The magnitudes of 245 earthquakes are disclosed (Swiss Seismological Service). Using these data, the total induced earthquake energy of 245 earthquakes was calculated to be 12.5 GJ.

Table 2 shows the total induced earthquake energy Et (GJ) of 6 sites.

Table2: Total induced earthquake energy

Site	Et (GJ)
Hijiori	0.0002
Ogachi	0.06
Newberry	4.1
Soultz	6.8
Cooper Basin	55.9
Basel	12.5

2.3 Relation of total water injection energy and total induced earthquake energy

Table 3 shows the calculation results of the ratio Et/Ei (%) of the total induced earthquake energy Et (GJ) to the injection energy Ei (GJ) at 6 sites, together with the maximum magnitude.

Table 3: Ratio Et/Ei (%) and maximum magnitude

Site	Ei(GJ)	Et(GJ)	Et/Ei(%)	Max. Mag.
Hijiori	46.6	0.0002	0.0004	0.3
Ogachi	189	0.06	0.03	2.0
Newberry	347	4.1	1.2	2.6
Soultz	300	6.8	2.3	2.6
Cooper Basin	879	>56	6.4	3.7
Basel	288	12.5	4.3	3.4

The relationship between the injection energy Ei and the ratio Et/Ei is shown in Figure 2.

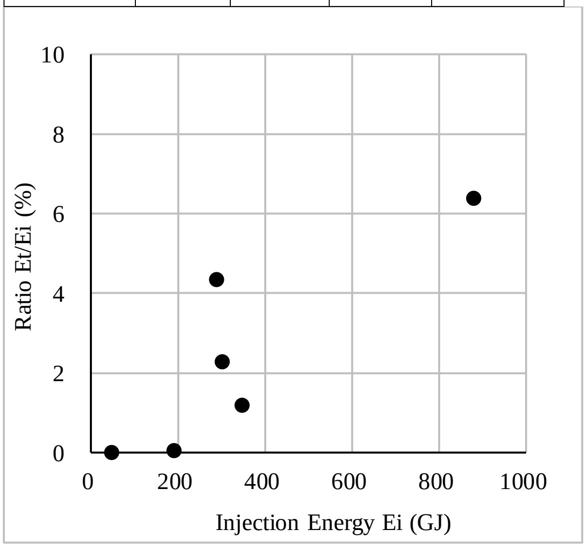


Figure 2: Ratio Et/Ei vs. injection energy

The ratios Et/Ei at Hijiori and Ogachi sites are very low as 0.0004 to 0.03%, and quite different from the ratios at other 4 sites.

2.4 Critical water injection energy of induced earthquake

Figure 3 shows the water injection energy per day and induced earthquake energy per day against the elapsed days at 4sites in Newberry, Soultz, Cooper Basin and Basel. The earthquake energy at 2 sites in Hijiori and Ogachi is very low and no figure on the relation of Ei and elapsed time is shown here, because a meaningful figure can't be obtained.

The results shown in Fig. 3 are summarized below.

2.4.1 Newberry

The induced earthquake of magnitude 1.5 occurred on the 16th day after the start of water injection, the cumulative water injection energy Eit until the 16th day was 74 GJ, and the cumulative induced earthquake energy Est was 0.016 GJ.

2.4.2 Soultz

The induced earthquake of magnitude 2.2 occurred on the first day after the start of water injection, the cumulative water injection energy Eit at the first day was 2.5 GJ, and the cumulative induced earthquake energy Est was 0.57 GJ.

2.4.3 Cooper Basin

The induced earthquake of magnitude 3.3 occurred on the 4th day after the start of water injection, the cumulative water injection energy Eit until the 4th day was 170 GJ, and the cumulative induced earthquake energy Est was 5.6 GJ.

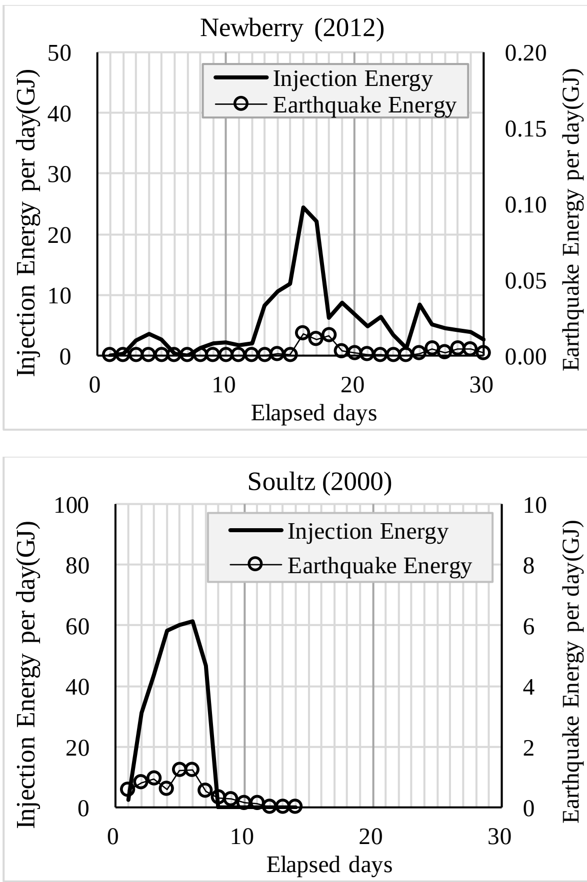
2.4.4 Basel

The induced earthquake of magnitude 1.6 occurred on the 2nd day after the start of water injection, the cumulative water injection energy Eit until the 2nd day was 4.1GJ, and the cumulative induced earthquake energy Est was 0.084GJ.

The ratio of the cumulative induced earthquake energy Est to the cumulative water injection energy Eit that generated the first induced earthquake was calculated. The results are shown in Table 4.

Table 4: Total water injection energy to induce first large earthquake

Site	Mag.	Eit(GJ)	Est(GJ)	Est/Eit(%)
Newberry	1.5	74	0.016	0.02
Soultz	2.2	2.5	0.57	22.8
Cooper Basin	3.3	170	5.6	3.3
Basel	1.6	4.1	0.084	2.0



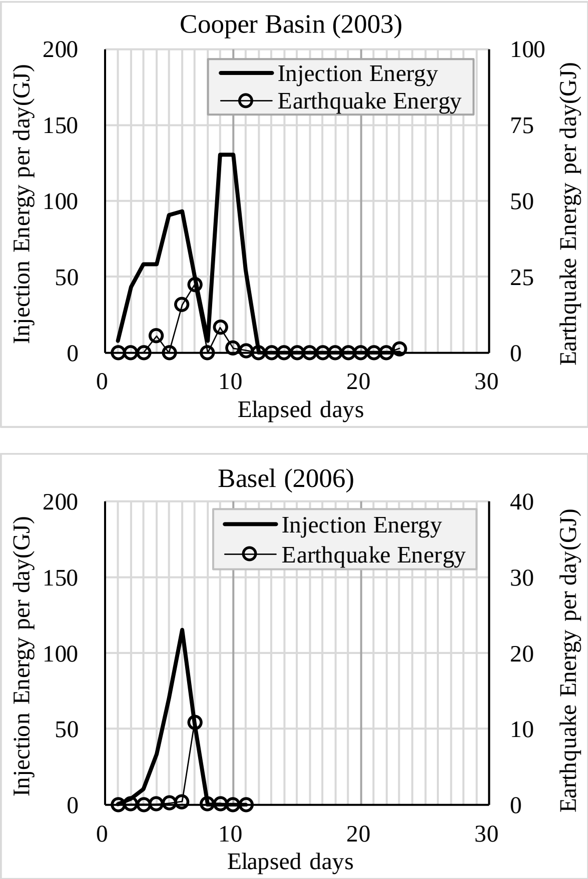


Figure 3: Injection and earthquake energy per day

3. DISCUSSION

The ratio of the total induced earthquake energy to the injection energy of hydraulic fracturing varies from site to site. It is thought to be due to the difference in the underground structure and rock properties.

The ratios Et/Ei at Hijiori and Ogachi sites are significantly different from the other 4 sites, and are very small as 0.0004 to 0.03% shown in Table 3. It seems that there are many pre-existing natural fractures and voids, therefore it is unlikely that large earthquakes will occur. However, because there are many natural fractures, the injected water can easily diffuse to surroundings and the water recovery rate in water circulation for power generation is low.

As the ratios Et/Ei of total induced earthquake energy at 4 sites of Newberry, Soultz, Cooper Basin and Basel are as high as 1.2 to 6.4%, the large earthquake will possibly occur if total and/or intensity of water injection energy becomes higher.

The ratios Et/Ei of total induced earthquake energy to total water injection energy at Hijiori and Ogachi sites were from 0.0004 to 0.03% and on the order of 1/100 or less of the ratios at 4 sites of Newberry, Soultz, Cooper Basin and Basel. These low values are almost same as the average ratio of about 0.01% reported for the shale gas production at British-Columbia, Canada (Boroumand and Eaton, 2012). This means that the underground structures at Hijiori and Ogachi sites may resemble that at British-Columbia shale gas plant.

The ratio Est/Eit varies largely from 0.02 to 22.8%, depending on sites as shown in Table 4. The induced earthquake with magnitude of 2.2 occurred by small water injection energy of 2.5 GJ at Soultz site and the ratio Est/Eit is 22.8%, which is higher than the ratio at other 3 sites. The reason for the difference can be due to the difference in underground structure.

As a result of analysis of hydraulic fracturing from the viewpoint of energy, information on the underground structure was obtained. By collecting the data of geological core samples and clarifying the relationship between hydraulic fracturing condition, permeability and induced earthquakes, the following 4 terms can be realized and efficient HDR system can be designed.

1) Effective creation of reservoirs

By understanding the properties of geological core samples such as crystal structure, density and hardness, and also size, form and distribution of natural fractures together with water injection energy and the permeability, then the conditions of effective hydraulic fracturing can be clarified.

2) Reduction of occurrence of induced earthquakes

By analyzing hydraulic fracturing energy on the site where HDR will be constructed, the occurrence of induced earthquakes can be suppressed by adjusting water injection energy.

3) Improvement of water recovery rate

Water recovery rate affects the power generation cost. By clarifying effects of the size and density of natural fractures on water recovery rate, appropriate measures can be devised to improve water recovery rate. High water recovery rate leads to low power generation cost.

4) Lifetime of reservoir

By obtaining information of underground structure and temperature and thermal conductivity of rock, the lifetime of a reservoir can be estimated.

4. CONCLUSION

By analyzing the hydraulic fracturing energy and the induced earthquake behavior during HDR experiments, useful information was obtained for efficient HDR design.

The ratios of induced earthquake energy to water injection energy at 6 sites were classified into 2 groups: the low ratio group (0.0004 to 0.03%) and the high ratio group (1.2 to 6.4%).

It was found the induced earthquake with large magnitude occurred in the high ratio group, and the water recovery rate was low in the low ratio group.

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