Micro-earthquake Observation Results in the Ogachi HDR Project

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Keywords: Micro-earthquake, Hot Dry Rock, Reservoir, Hydraulic stimulation, Flow path

ABSTRACT

In the Ogachi HDR project, two reservoirs were created by hydraulic fracturing operations at different depths of 719 and 1,000 m from a 1,000 m deep injection well. Location and size of the reservoirs have been evaluated by induced micro-earthquakes hypocenter distribution. The reservoirs were estimated to progress in different directions. It was difficult to penetrate these reservoirs by a production well. Therefore the production well did not penetrate the best flow paths in the reservoirs and the water recovery rate of produced water to injected water was so small. Hydraulic stimulation operations in the both injection and production wells were conducted to enlarge water flow paths between the wells and to improve the recovery rate. Comparing the tracer test results before and after the stimulation operations, short paths between the injection and the production wells were estimated to occur. From the micro-earthquakes observation results the short path was created from the bottom of the injection well to the bottom of the production well. This short path in the production well was confirmed by the temperature logging results. Sand plug was set in the bottom of the injection well to conduct individual flow tests between the two wells through the two reservoirs. The tracer test results before and after the individual flow tests showed that the short paths were partially plugged. These results show that the flow paths in the HDR reservoir are very sensitive to hydraulic operations.

1. INTRODUCTION

The Central Research Institute of Electric Power Industry (CRIEPI) has conducted a Hot Dry Rock (HDR) program at Ogachi, northern Japan from 1989 to 2002. The program aimed to create multiple reservoirs from one well and to demonstrate heat extraction from the multiple reservoirs. An injection well (OGC-1) was drilled to a depth of 1,000m and a rock temperature at the bottom of OGC-1 was measured 228 °C. Two HDR reservoirs were created at different depths of around 719 m and 1,000 m of OGC-1 (Kaieda et al., 1993). During these reservoir creation operations, micro-earthquake events were monitored and located by a 10-station network. Many numbers of micro-earthquake events were observed and analyzed not only to estimate the location and extension of created reservoirs but also to estimate the stress condition and significant structure in the reservoirs (Kaieda et al., 2005). According to the event hypocenter distribution, a production well (OGC-2) was drilled in 1992 directionally to intersect both the reservoirs.

Some water circulation tests have been performed from OGC-1, through the reservoirs, to OGC-2. A 5-month water circulation test was performed in 1994. In this test water recovery rate was so small of 10 % that OGC-1 was stimulated by hydraulic fracturing in 1995. A 1-month water circulation test was performed in succession to this stimulation. During this test water recovery rate increased to 25 % (Ito et al., 2001). In 1997, a sand plug was set below the upper reservoir in OGC-1 to conduct a water circulation test between OGC-1 and OGC-2. The water was recovered form OGC-2 in this circulation test. After the sand plug was removed from OGC-1 a water circulation test was conducted between OGC-1 and OGC-2 through both the upper and lower reservoirs. In this circulation test the water recovery rate was 15 % (Kaieda et al., 2012).

During these water circulation tests tracer tests were conducted to evaluate water flow conditions in the reservoirs during these water circulation tests. The tracer test analysis showed that the characteristics of the reservoir changed by the water circulation and hydraulic stimulation operations (Kiho et al., 1999, Kiho, 2000).

It is necessary for extracting heat effectively from HDR system to evaluate the water flow characteristics in the each reservoir of multiple reservoirs and to control water flow balance in the reservoirs. Previous study showed that water flowed through the lower reservoir dominantly at Ogachi (Kaieda et al., 2012). The author analyzed micro-earthquake hypocenter location more accurately using detonation shot data which was conducted in 1995. From the recent analysis of the tracer tests and micro-earthquakes observation, the location of the main water flow path between OGC-1 and OGC-2 was estimated and the flow path characteristics change after the stimulation operations was evaluated.

2. HDR RESERVOIR CREATION AND WATER CIRCULATION AT THE OGACHI SITE

Figure 1 shows the concept of the program at Ogachi. The geology of the Ogachi site consists of the Cretaceous granodiorite covered with Tertiary lapilli tuff to a depth of 300m from the ground surface. OGC-1 was drilled into pre-Tertiary granitic rock in 1990. The well reached a depth of 1,000m and a rock temperature of 228 °C. OGC-1 was completed with casing to a depth of 990 m and the bottom of 10 m interval from 990 m to 1,000 m was left uncased with a diameter of 86 mm. A first (lower) reservoir was created in 1991 by injecting a total of 10,163 ton of water into a bottom 10-m open-hole interval. During this reservoir creation water was injected at a maximum well-head pressure of 19 MPa and at an average flow rate of 500 kg/min. After the first reservoir creation, an interval from 711 to 719 m of the casing in OGC-1 was milled as a window. A sand plug was set below the window of OGC-1. A second (upper) reservoir was created in 1992 by injecting a total of 5,400 ton of water into the window of OGC-1. During this upper reservoir creation, water was injected at a maximum well-head pressure of 22 MPa and at an average flow rate of 400 kg/min. (Kaieda et al., 1993). After the upper reservoir creation, the sand plug was removed from OGC-1. Then water can flow into both upper and lower reservoirs.
According to the micro-earthquake analysis observed during the reservoir creation operations, the upper and the lower reservoirs extended to different directions, almost 90 degree difference, as described in section 3. OGC-2 was drilled in 1992 directionally to intersect both the reservoirs as a production well, but OGC-2 did not penetrated best points in the reservoirs. Particularly, the trajectory of OGC-2 passed through the edge of the upper reservoir distribution estimated by the micro-earthquake hypocenter locations.

A first water circulation test was conducted by injecting surface water into OGC-1 and the water recovered from OGC-2 through the reservoirs in 1993. Because water recovery rate during the circulation test was so small of a few % that OGC-1 and OGC-2 were stimulated by hydraulic fracturing to improve water flow condition in the reservoirs in 1994. In the 1994 stimulation water was injected into OGC-2 at a flow rate of 750 kg/min and at a well-head pressure of 13 MPa. After the OGC-2 stimulation water recovery rate from OGC-2 increased to 10 % during the 5-month water circulation test was performed from OGC-1, through the reservoirs, to OGC-2 in 1994. Water recovery rate from OGC-2 was still so small and water injection pressure was so high that OGC-1 was re-drilled and both of OGC-1 and OGC-2 were stimulated by hydraulic fracturing in 1995.

In 1995 OGC-1 was re-drilled from 1,000 m to 1,027 m to increase the water injection interval. After this drilling, OGC-1 and OGC-2 were stimulated by injecting water into OGC-1 at a flow rate of 1.75 ton/min and at a well-head pressure of 18 MPa, and water into OGC-2 at a flow rate of 2.25 ton/min and at a well-head pressure of 18 MPa.

A 1-month water circulation test was performed in succession to these stimulation operations. During this circulation test water recovery rate increased to 25 % and the water injection pressure at well-head of OGC-1 decreased less than 10 MPa at a flow rate of 500 kg/min. In 1997, a sand plug was set in OGC-1 to conduct a water circulation test between OGC-1 and OGC-2 through only the upper reservoir to estimate which reservoir, upper or lower, is dominant as flow path. No water was recovered from OGC-2 in this circulation test. After the sand plug was removed, a water circulation test was conducted between OGC-1 and OGC-2 through both the upper and lower reservoirs. During this water circulation test hot water and steam was recovered from OGC-2 at a recovery rate of 15 %. Another production well (OGC-3) was drilled in 2000 (Kaieda et al., 2005). Using OGC-3 many hydraulic tests and temperature monitoring were performed with the fiber-optic thermometer. But no water circulation test was conducted using OGC-3, because the budget for the program was cut in 2003 (Kaieda et al., 2012).

![Figure 1: Concept of the Ogachi HDR experiments. OGC-1 is the injection well. OGC-2 and OGC-3 are the production well.](image)

### 3. MICRO-EARTHQUAKE OBSERVATION

#### 3.1 Micro-earthquake observation system

Micro-earthquakes were monitored by a 10-station network of three-component geophones (natural frequency of 5 Hz, sensitivity of 1.6 V/cm/s) installed in 30- to 50-m deep boreholes and by a three-component geophone (overall sensitivity of 316 V/cm/s) set at a depth of 380 m in a 946 m deep observation well (Nagano et. al., 1994). Signals detected by these geophones were transferred to a measurement house by six-conductor cables, band-pass filtered between 10 Hz (or 30 Hz) and 1 kHz, and digitized by 2 kHz sampling (Kaieda and Sasaki, 2002).

Micro-earthquake event locations were calculated by inversion of P-wave arrival times. Arrival times were picked by hand from digital seismograms. The velocity structure (a flat layers model) under the Ogachi site was obtained by the seismic reflection survey on a line crossing the site. The P-wave velocity from the surface to a depth of 224 m was 2.6 km/s, from 224 m to 465 m was 3.7 km/s and below 465 m was 5.0 km/s. Station correction values for compensating heterogeneity of the velocity structure were...
obtained by a 1-kg explosive detonation conducted at a depth of 995 m in OGC-1. An example of the waveforms observed at all stations generated by the shot is shown in Figure 2.

Recent analysis of error of event locations showed that the detonation shot location which was located by the micro-earthquake location method was determined at 22.6 m west, 13 m north and 6.7 m deep from the logging location, respectively (Kaieda et. al., 2000). Using these results, the station correction values were re-determined and the previous micro-earthquake event locations were re-calculated.

Figure 2: An example of the waveforms of vertical component observed at all observation stations generated by a 1-kg detonation shot at a depth of 955 in OGC-1.

3.2 Observation results
Many micro-earthquake events were observed during the reservoir creation operations. During the lower and upper reservoir creation operations 1,513 and 1,041 events were located, respectively as shown in Figure 3. The minimum magnitude of the events being located in the lower and the upper reservoir creation operations was -3.6 and -4, and the maximum was 2.5, 0.9, respectively. Except two large events having magnitude of 2.5 and 1.6 in the lower reservoir creation, magnitude of all events was smaller than -1. Event magnitudes observed in the upper reservoir creation were relatively larger than those in the lower. The 1 kg explosive detonation shot at a depth of 995 m on OGC-1 was determined as a magnitude of -1.5. From this distribution the lower reservoir was estimated to extend about 200 m thick and about 500 m wide, propagating 1,000 m in the NNE direction, and the upper reservoir was 200 m thick and about 400 m wide, propagating ESE direction. The two reservoirs extended different directions at only 300 m different depths (Kaieda et al., 2000). This difference was considered because of natural joints characteristic differences at the depths (Ito and Okabe, 2001). The main flow path in the lower reservoir was estimated NNE and the upper was east from OGC-1, respectively by applying the collapsing method to the micro-earthquake hypocenter location distribution (Kaieda et al., 2002).

OGC-2 was drilled to a measured depth of 1,100 m as a production well in order to intersect the both reservoirs. OGC-2 was completed with casing pipes by cementing to a depth of 700 m and left uncased with a diameter of 98 mm from 700 m to 1,100 m (bottom). It was difficult to intersect the both reservoirs by one production well, because the reservoir extension directions were completely different, almost 90 degree. The trajectory of OGC-2 was determined that the well head was located at SE from OGC-1 and drilled vertical to a depth of 300 m then directionally drilled to the north. The bottom of OGC-2 was located at about 80 m NE from OGC-1.
Figure 3: Micro-earthquake hypocenter distribution in the lower and upper reservoirs creation. The upper left is the map view and the lower left is cross section view looking north in the lower reservoir creation in 1991. The upper right is the map view and the lower right is cross section view looking north in the upper reservoir creation in 1992. During the 1995 stimulation operation in OGC-1 the observed micro-earthquake event locations distributed from OGC-1 to near bottom of OGC-2 as shown in Figure 4. This distribution means that the near the bottoms of OGC-1 and OGC-2 in the lower reservoir were more stimulated than the upper.

Figure 4: Micro-earthquake hypocenter distribution during the OGC-1 hydraulic stimulation in 1995. The left figure is the map view and the right is the cross section view looking west.

4. TRACER TESTS

4.1 Tracer test operation
In 1994, 150g of NaFl (Sodium Fluorescein) was dissolved in 350 kg water. The NaFl dissolved water was injected into OGC-1 and concentration of the fluorescein in the produced water from OGC-2 was measured during the water circulation test. Background value of concentration of NaFl in OGC-2 before the NaFl dissolved water injection was 0.05 ppb. 500 g NaFl was dissolved in 350 kg of water for the 1995 tracer test. NaFl concentration before the tracer test was measured 4.33 ppb. In 1997 NaFl concentration background value was measured 0.3 ppb before the tracer test and 500 g NaFl was dissolved in 350 kg of water as a tracer.

4.1 Tracer test results
In 1994 tracer test after three hours from the tracer injection, fluorescein concentration in produced water increased rapidly and the concentration showed a small peak of 6.17 ppb at 20 hours and another large peak of 12.39 ppb at 83 hours after the tracer injection started (shown A and B in the upper graph of Figure 4, respectively). Response curves obtained from the tracer monitoring involves two curves due to the two reservoirs. A numerical simulation with a two-flow path model showed to separate the response curve each other. Modal volumes of the upper and lower reservoirs are estimated 8.4 m³ and 289 m³, respectively. In 1995 tracer test fluorescein concentration rapidly increased at 5.5 hour after tracer injection and reached to a peak of 310.59 ppb at 18 hours after the injection then decreased gradually (shown in the middle graph of Figure 4). Modal volumes of the upper and lower reservoirs are estimated 6.6 m³ and 117 m³, respectively. In 1997 tracer test 11 hours after the tracer injection, fluorescein concentration in
produced water from OCG-2 suddenly increased, reached to a peak of 80.02 ppb at 44 hours after the tracer injection and decreased gradually (shown in the bottom graph of Figure 5). Because response curves of the 1997 test showed not clear two reservoirs response, a mode volume of the upper and lower reservoirs was estimated 138 m$^3$ as one reservoir (Kiho et al., 1999).

Through the circulation tests, the modal volume of the lower reservoir decreased gradually from 1994 to 1995, and in 1997 test the modal volume increased. This may be caused by new fracture creation in the lower reservoir in the stimulation operations before the circulation tests. The results showed that there were two peaks in the tracer concentration curve with time at earlier circulation test but one of the peaks became not clear and only one peak was detected in the later test. This may mean the flow paths in the reservoirs changed from two dominant paths to one (Kiho et al., 1999). Value of width at 1/2 height which is assumed to represent dispersion of the reservoir decreases between 1994 and 1995, but the value increases in 1997. This increase is considered to be caused by the plugging the fracture with the sand which is used in the flow test in which only the upper reservoir was used for the circulation test in 1997.

![Figure 5](image-url)

**Figure 5:** Tracer test results. The upper figure is fluorescein concentration with cumulative flow volume from OCG-2 during the 1994 water circulation test. The middle and the bottom are the results of fluorescein concentration in the 1995 and 1997 tracer tests, respectively.

**5. MAIN WATER FLOW PATHS**

Temperature measurements were conducted in OGC-2 before the water circulation test in 1993 and after the water circulation test in 1997. Temperature in OGC-2 increased linearly with depth in the 1993 result, but some anomalies were observed in the 1997 result as shown in Figure 5. Temperature below the depth of 700 m in 1997 decreased about 2 to 6 degree C from 1993 results. Temperature at 730 m and 1,070 depths in 1997 decreased 9 and 18 degree C, respectively. These results mean that the rock temperature decreased by the water circulation tests and relatively large water flow occurred at 730 m and 1,070 m depths.

Considering with micro-earthquake observation and tracer test results, a dominant water flow occurs from near the bottom of OGC-1 to a depth of 1,070 m in OGC-2 and this flow path must be a short path in the lower reservoir created by the hydraulic stimulation operations. However the flow path might be partially plugged by sand particles which were used for the circulation test between OGC-1 and OGC-2, only through the upper reservoir in 1997.
CONCLUSION

Two artificial reservoirs were created at different depths of around 719 m and 1,000 m in OGC-1. Because the two reservoirs extended different directions, a production well OGC-2 did not intersect best points of the reservoirs. Therefore water recovery rate during water circulation tests were so small that hydraulic stimulation was applied to OGC-1 and OGC-2. After these stimulation operations, water recovery rate during the water circulation tests increased. Comparing the tracer test results before and after the stimulation operations, a short path between OGC-1 and OGC-2 was estimated to occur. The short path was located from near bottom of OGC-1 to a depth of 1,070 m in OGC-2 by the micro-earthquake observation and the temperature logging results in OGC-2. The tracer test results before and after the individual flow tests showed that the short path was partially plugged. This may be caused by partial plugging with sand particles which was used for the circulation test between OGC-1 and OGC-2 through only the upper reservoir in 1997. These results show that the flow paths in the HDR reservoir are very sensitive to hydraulic operations.

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