INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Missing Water at the Aratozawa Dam due to the Iwate-Miyagi Nairiku Earthquake in 2008

T. Ohmachi
Japan Dam Engineering Center, Tokyo, Japan
ohmachi@jdec.or.jp

M. Kohayakawa
Yokohama City, Yokohama, Japan

ABSTRACT:
The Aratozawa dam which is a 74.4 m high rockfill dam with a central clay core was located in the near-field of the Iwate-Miyagi Nairiku Earthquake in 2008 (M_J 7.2), Japan. Despite little damage to the dam body, a large volume of storage water in excess of 200,000m^3 disappeared from the reservoir during 4 days after the main shock. The causes of the water is discussed based on daily records of such as the earthquake-induced pore-water pressure and seepage water pressure observed at the dam foundation.

Keywords: 2008 Iwate-Miyagi Earthquake, Aratozawa dam, pore water pressure, seepage water pressure, reservoir water

1. INTRODUCTION

The Iwate-Miyagi Nairiku Earthquake (M_J7.2) occurred at 8:43 a.m. on June 14, 2008 with its focus 8km deep below southwestern Iwate Prefecture, Japan (Japan Meteorological Agency, 2008). Several dams, in the near field of the earthquake, were strongly shaken by the main shock as well as by many aftershocks. Among them was the Aratozawa dam, which is a 74.4 m high rockfill dam constructed mainly for irrigation and flood control purposes. The dam was located 15km south of the epicenter of the main shock. Figure 1 shows a location map of the earthquake epicenter, the Aratozawa dam and an estimated seismic fault plane.

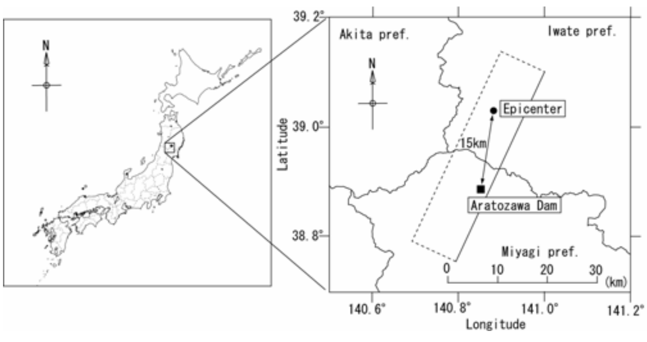


Figure 1. Location map of the epicenter of the 2008 Iwate-Miyagi Nairiku earthquake and the Aratozawa dam. The estimated seismic fault plane is indicated by the dashed lines.

The plan and cross sections of the Aratozawa dam are shown in Fig. 2. The dam has a crest length of 413.7 m, a crest width of 10 m, and the dam body consists of 5 zones; core, filter, transition, inner rockfill, and outer rockfill. The seismic coefficient method with a horizontal coefficient of 0.15, was used for the seismic design of the dam. Work of the embankment dam body was virtually completed in 1991, and was followed by construction of appurtenant structures and impounding tests. The whole scheme was completed in 1998.

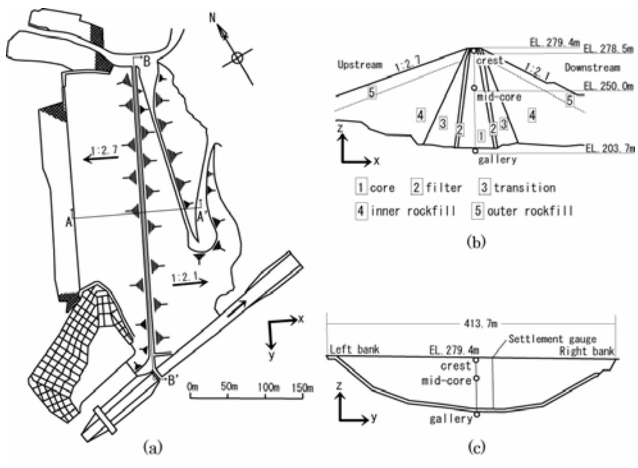
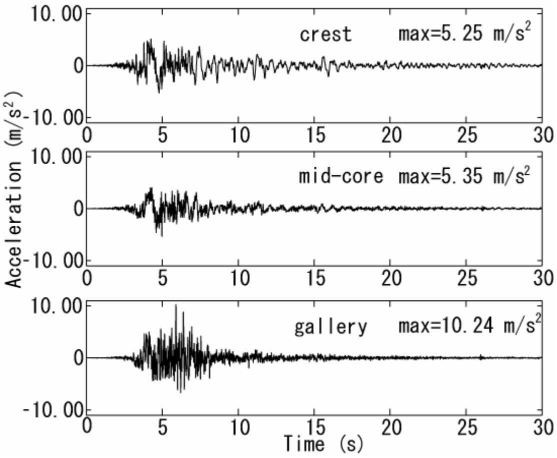
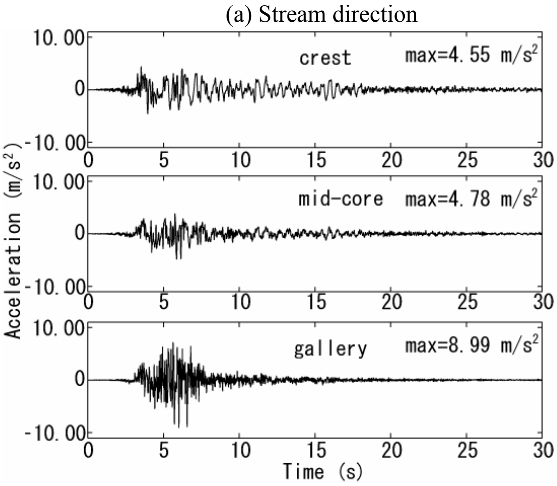


Figure 2. (a) Plan, (b) cross section A-A' and (c) cross section B-B' of the dam with seismometers location at crest, mid-core and gallery.

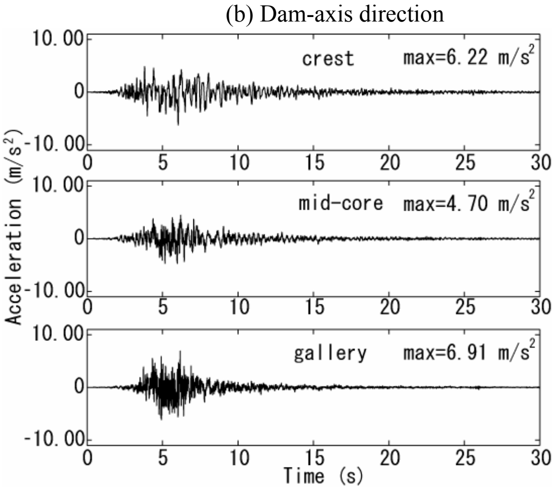
Three component strong motion accelerometers are installed at three locations, i.e., the dam crest, the mid-core and the bottom gallery (see Fig. 2). During the main shock, strong motion accelerometers installed at the Aratozawa dam registered a peak acceleration of 10.24 m/s^2 at the bottom gallery. As shown in Fig. 3 and Table 1, in each direction, the peak acceleration at the bottom gallery was the largest. This seems unusual, since earthquake acceleration at a crest is usually the largest due to the amplification effect of the dam body. But this attenuation in acceleration is attributed to the nonlinear characteristics of soil materials. Actually, peak periods in spectral ratios between the crest and the gallery were significantly longer during the main shock than those in other smaller earthquakes (Ohmachi and Tahara, 2011).



(a) Stream direction



(b) Dam-axis direction



(c) Vertical direction

Figure 3. Time histories of three-component strong motion acceleration of the main shock observed at three locations shown in Fig. 2**.**

Table 1. Peak acceleration observed during the main shock (m/s^2)

Location of accelerometer	Stream direction	Dam-axis direction	Vertical direction
Dam crest	5.25	4.55	6.22
Mid-core	5.35	4.78	4.70
Gallery	10.24	8.99	6.91

Despite such a high acceleration, the dam remained in a safe and stable condition, with minor damage to the dam body like cracks in the asphalt pavement observed at the right bank corner of the crest. Nevertheless, reportedly, a large volume of the storage water was found to be lost or disappeared from the reservoir during a couple of days after the main shock (Kato, 2009). Since the whereabouts of the lost water has been still unknown, the water is called the missing water in the present study.

When it comes to earthquake-induced hydrological changes in the near-field of earthquakes, they are usually observed and discussed in terms of such changes as in water table, temperature and content of the ground-water. In the present study, however, in addition to records of the downstream river flow, those of pore water pressure and seepage water pressure at the dam foundation are used to estimate causes and effects of the missing water.

2. MISSING WATER EVALUATED AT THE ARATOZAWA DAM

At the time of the main shock, the reservoir water level was at EL.268.48 m, while the high water level is at EL.274.4 m (see Fig. 7). As shown in Fig. 4, extensive landslides with a total volume of about 67 million m^3 occurred upstream of the dam, and a substantial part of that volume collapsed into the reservoir, resulting in a sudden rise of 2.4 m in the reservoir water level. This rise in the water level was equivalent to an increase in storage water volume of 1.5 million m^3.

The missing water volume Q was calculated by,

$$Q = \Delta S - O + I \qquad (1)$$

where ΔS is a change in the reservoir water volume obtainable from a relation between the reservoir water level H and the reservoir water volume V which is hereinafter referred to as the H-V relation, O is the water volume of the outflow discharge observed at the dam and I is the water volume of the inflow into the reservoir.

Figure 4. The Aratozawa dam (right) and extensive landslides that occurred upstream of the dam (left)

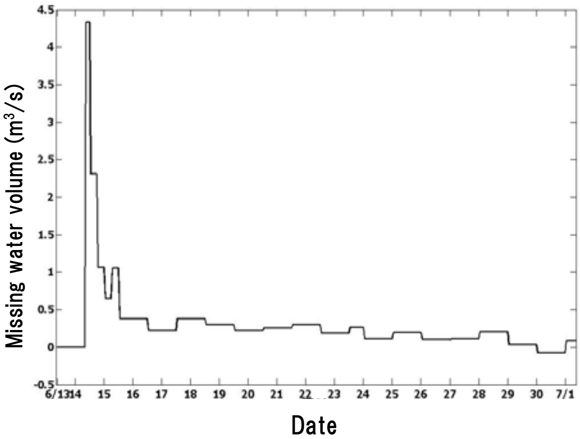


Figure 5. Temporal change in the missing water volume during June 14 and July 1, 2008, calculated by Eq. 1.

The H-V relation was slightly changed after the earthquake due to the above-mentioned landslide and co-seismic displacement of the ground. Although the change was neglected in the previous evaluation (Kato, 2009), we recalculated Q taking into account the new H-V relation with a result shown in Fig. 5. Figure 5 indicates that the missing water was in excess of 4 m^3/s immediately after the main shock, but that it decreased rapidly to almost zero in a couple of days. The total volume of the missing water obtained from Fig. 5 amounted to about 200,000 m^3.

As for the whereabouts of the missing water, absorption into the soil mass that collapsed into the reservoir was supposed on little evidence (Kato, 2009). In the meantime, daily records of the earthquake-induced pore water pressure and seepage water pressure observed at the dam foundation are used in the present study.

3. PORE WATER PRESSURE BEFORE AND AFTER THE MAIN SHOCK

Pore water pressure has been measured to record daily at 9:00 a.m. at the Aratozawa dam. The pore water pressure distribution in a vertical section of the central part of the dam was estimated from readings of the meters before and after the main shock, as shown in Fig. 6 where small circles indicate locations of the meters and a simple distribution is assumed on the upstream side. The vertical section is the cross section A-A' where the seismometers are installed (see Fig. 2). The numbers in the foundation indicate the pressure readings in terms of kPa.

In the core zone of the dam, the pore water pressure of June 13, 2008 (denoted by 2008/6/13) was distributed in the typical pattern of a normal steady state condition, although the estimated phreatic line was not as smooth as expected, maybe due to some mechanical errors included in the readings. On June 14, seventeen minutes after the main shock, the distribution pattern had remarkably changed to exhibit a sudden build-up of excess pore water pressure in the core zone especially at the lower part of the zone. Figure 7 shows a series of the daily readings of the pore water pressure meter #16 whose location is indicated by a solid circle in Fig. 6. It can be seen that after the main shock, with a continuous drawdown of the reservoir water level, the pore water pressure showed a monotonous decrease. Seemingly, after June 24, 2008, the decrease in the pore water pressure in the core zone was mainly governed by the drawdown of the reservoir water level.

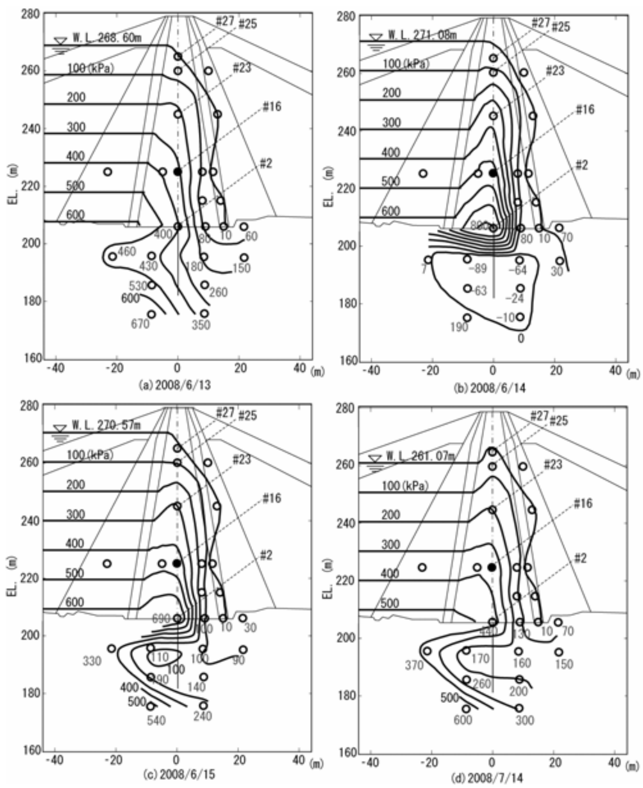


Figure 6. Distribution of pore water pressure in the clay core and foundation. Small circles indicate locations of pore water pressure meters in the core and foundation.

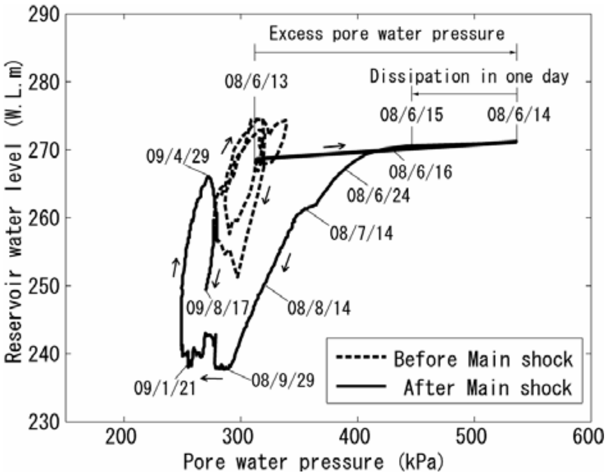


Figure 7. Time history of pore water pressure in the clay core at meter #16 plotted against reservoir water level

Meanwhile in the dam foundation, Fig. 6 indicates that, immediately after the main shock, in contrast to the excess pore water pressure in the core zone, the negative pore water pressure was produced, especially in the vicinity of the grout curtain. The negative pressure almost disappeared by June 15, one day after the main shock. On June 17, three days after the main shock, the pore water pressure distribution in the foundation almost approached the normal steady pattern observed before the main shock.

Figure 9 shows a series of daily readings of the pore water pressure meters in the dam foundation whose locations are shown in Fig. 8, together with the temporal change in the missing water volume (see Fig.5). Immediately after the main shock, almost all the pore water pressure meters showed a remarkable drop, and then turned to a monotonous increase toward the steady sate of the pore water pressure. It is interesting to note that the pressure meters at PR-8 and 10 whose locations are just below the foundation surface, did not show such a remarkable decrease in the pore water pressure as others in the foundation. In addition, obviously there was a negative correlation between the temporal changes in the pore water pressure in the dam foundation and the missing water volume.

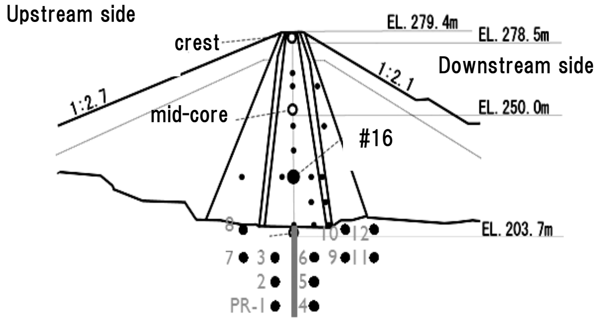
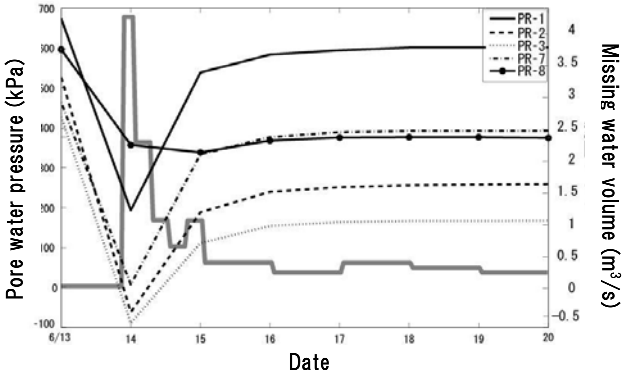
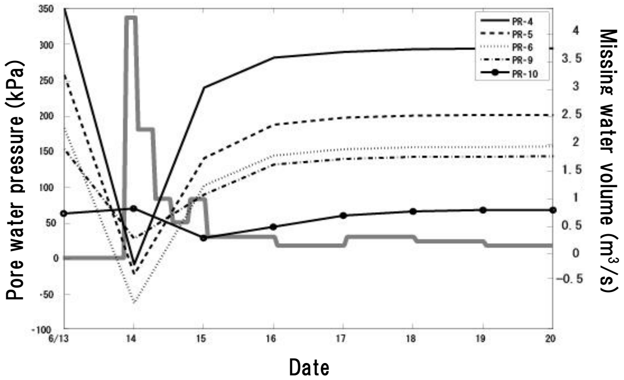


Figure 8. Location of pore pressure meters in the dam foundation (section A-A')



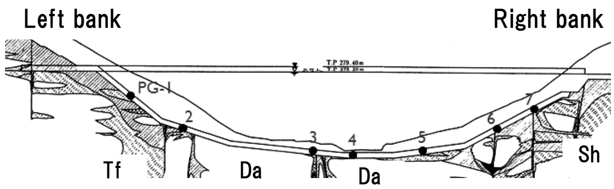
(a) Pore water pressure in the upstream foundation



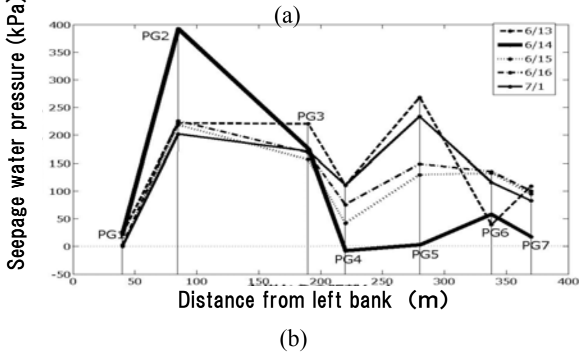
(b) Pore water pressure in the downstream foundation

Figure 9. Daily readings of the pore water pressure meters in the dam foundation during June 13 and 20, 2008 compared with the change in the missing water volume shown in Fig. 5.

4. SEEPAGE WATER PRESSURE BEFORE AND AFTER THE MAIN SHOCK



(a)



(b)

Figure 10. (a) Vertical section along the bottom gallery, and (b) distribution of seepage water pressure along the gallery

As shown in Fig. 10 (a), seepage water pressure meters PG-1 through 7 are installed at 7 points on the downstream side along the bottom gallery of the dam, and their daily readings were recorded at 9:00 a.m. The daily readings of the meters on June 13, 14, 15, 16, and July 1 are shown in Fig. 10 (b). Apparently, immediately after the main shock, the seepage water pressure showed a sudden decrease on the right half side of the dam, while it showed a sudden increase on the left half side. In half a month after the main shock, as a whole, the decreased or increased readings of the seepage water pressure almost returned to those observed before the main shock.

As far as the daily readings of the pore water pressure and seepage water pressure are concerned, it seems reasonable to think that the missing water was absorbed into the dam foundation, especially on the right half side of the dam. A geological profile along the gallery (Oh-ishi, 1975) is roughly shown in Fig. 10 (a). The bedrock in the dam foundation consists mainly of hard dacite (denoted by Da) of the rock class C_H～B. On the left bank side, solid tuff (Tf) of the class C_M～C_H is underlain with somewhat soft layers of shale (Sh) and tuff of the class C_M. On the right bank side, hard dacite is underlain with somewhat soft layers of shale and tuff of the class C_M～C_H. As shown in Fig. 10 (a), some parts of vertical joints on the right bank side are weathered to the class C or D denoted by dark hatches.

5. DOWNSTREAM RIVER FLOW

At the Monji station located about 500 m downstream of the Aratozawa dam, the river water depth D was measured at every one hour. The river flow F was evaluated from the measured depth D, based on a relation between D and F. The river flow F at the Monji station consists of two parts expressed as,

$$F = O + C \quad (2)$$

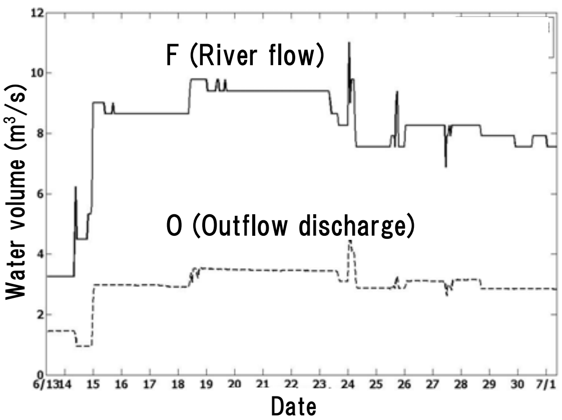


Figure 11. Time histories of the downstream river flow at the Monji station and outflow discharge.

where O and C are the outflow discharge at the Aratozawa dam, and catchment from the basin between the dam and the Monji station, respectively. The latter remains almost constant during a period of fine weather.

The time histories of the river flow F and outflow discharge O are shown in Fig. 11 during June13 and July 1, 2008, with solid and broken lines, respectively. The difference between the two lines F and O in Fig. 11 is considered as the catchment C, and the difference shows a sudden increase after the main shock, maybe partly because of a slight change in the slope of the ground surface due to near-field effects of the earthquake. It should be noted in Fig. 11 that, in contrast to other days, on June 14 and 15, the river flow F had less correlation with the outflow discharge O, suggesting that a part of the missing water arrived at the Monji station.

6. DISCUSSION

In field investigations conducted immediately after the main shock, surface ruptures were observed at around northern and southern rims of the Aratozawa dam reservoir (Toda et al., 2010). Those at the north rim were close to the massive landslides shown in Fig. 4, and those at the south rim were found on the road running on the right bank side of the dam. Based on several ground breaks, a fault trace in the reservoir bottom crossing from the north to the south was estimated, even though it was not certain.

Figure 12. Upstream view of the right side of the Aratozawa dam and reservoir bottom when the reservoir water level was lowered in September, 2008.

As shown in Fig. 7, when the reservoir water level was lowered below EL.240m after the main shock as a part of the post-earthquake inspection, most part of the reservoir bottom was exposed to the air. As long as the visual inspection was concerned, neither the estimated fault traces nor ground holes and breaks from which the above-mentioned missing water was thought to be absorbed into the dam foundation was found anywhere. Thus, for the time being, the whereabouts of the missing water evaluated at the Aratozawa dam reservoir following the 2008 earthquake has been still unknown in detail.

However, immediately after the earthquake, not only the negative pore water pressure was produced in the dam foundation, but also the seepage water pressure on the right half side of the dam showed a sudden decrease. Hence, it seems natural to think that the negative pore water pressure and the sudden decrease in the seepage water pressure are attributed to the dilative ground strain resulting from the shallow seismic faulting (Kasahara et al., 2003). In addition, the temporal change in the missing water volume showed a remarkable correlation with the water pressure changes.

Consequently, even though the fault traces were not found on the ground surface of the dam site, majority of the missing water described here was probably caused by dilatation effects of the shallow seismic faulting of the earthquake.

7. CONCLUSIONS

Conclusions drawn from the present study are:

- A large volume of storage water of the Aratozawa dam in excess of 200, 000 m^3 disappeared from the reservoir during a couple of days after the main shock of the 2008 Iwate-Miyagi Earthquake of magnitude 7.2, Japan.
- During the main shock, in contrast to pore water pressure build-up in the clay core zone of the dam, the pore water pressure in the dam foundation showed a sudden decrease, especially around the grout curtain of the dam foundation.
- The decrease in the pore water pressure was so extensive that some of the pressure meters showed negative pressure. But the decreased pressure almost returned to the normal in a couple of days.
- The seepage water pressure meters installed downstream along the bottom gallery of the dam showed a sudden change due to the main shock. On the right half side of the dam, the change in the seepage pressure was a decrease, while it was an increase on the left half side. Both the decreased or increased seepage water pressure practically returned to the normal in half a month at most.
- Judging from a good correlation between both readings of the pore water pressure and seepage water pressure, the missing water was absorbed into the dam foundation, mainly on the right half side of the dam foundation within a couple of days after the main shock.
- In addition, a part of the missing water seemed to arrive at the Monji station immediately after the main shock.
- Probably the missing water was caused by dilatation effects of the shallow seismic faulting of the 2008 earthquake.

Incidentally, at the Aratozawa dam, there was no report of damage to the dam body or the missing water triggered by the main shock and a series of aftershocks of the 2011 off the Pacific coast of Tohoku Earthquake of magnitude M_w9.0 that took place on March 11, 2011.

ACKNOWLEDGEMENT

The authors would like to express their thanks to the civil engineers of the Miyagi Prefecture for providing information about the Aratozawa dam.

REFERENCES

Japan Meteorological Agency (2008）: Iwate-Miyagi Nairiku earthquake in 2008, http://www.seisvol.kishou.go.jp/eq/2008_6_14_iwate-miyagi/index.html.

Kasahara, J. Toriumi, M. and kawamura, K. (ed.) (2003): The role of water in earthquake generation, the University of Tokyo Press (in Japanese).

Kato, K. (2009): Functions of dams shared during the 2008 Iwate-Miyagi Nairiku earthquake, *Engineering for Dams*, (275), 60-67 (in Japanese)

Oh-ishi, S. (1975): Design and oractice of the Aratozawa dam, *Damu Nippon*, 15-47 (in Japanese).

Ohmachi, T. and Tahara, T. (2011): Nonlinear earthquake response characteristics of a central clay core rockfill dam, *Soils and Foundations*, Vol. 51, No.2, pp.227-238.

Toda, S., Maruyama, T. Yoshimi, M. Kaneda, H., Awata, Y., Yoshioka, T. and Ando, R.(2010) : Surface rupture associated with the 2008 Iwate-Miyagi Nairiku, Japan, earthquake and its implication to the rupture process and evaluation of active faults, *Zisin* (Journal of the Seismological Society of Japan) Vol. 2, No. 62, pp.153-178 (in Japanese).