Earth Planets Space, **60**, 1153–1159, 2008

Groundwater level changes related to the ground shaking of the Noto Hanto Earthquake in 2007

Satoshi Itaba[1], Naoji Koizumi[1], Norio Matsumoto[1], Makoto Takahashi[1], Tsutomu Sato[1], Ryu Ohtani[1], Yuichi Kitagawa[1], Yasuto Kuwahara[1], Takashi Sato[1], and Kunio Ozawa[2]

[1]*Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Higashi, Tsukuba, Ibaraki, Japan*
[2]*Disaster Prevention Bureau, Shizuoka Prefectural Government, Japan*

(Received July 9, 2007; Revised December 4, 2007; Accepted December 5, 2007; Online published December 10, 2008)

The Geological Survey of Japan, AIST has been monitoring groundwater using the observation network of about 40 stations in and around the Kinki and Tokai districts for earthquake prediction research. The Noto Hanto Earthquake in 2007 ($M_{\rm JMA}$ 6.9) occurred in the northwestern part of the Noto Hanto Peninsula, Japan on March 25, 2007. The epicentral distance to the nearest and furthest observation well is about 100 km and 400 km, respectively. Changes in groundwater level related to the Noto Hanto Earthquake were detected at many stations. Most of these were changes in the long-term trend and/or short-term oscillation; there were a few step-like changes. The coseismic static volumetric strain changes calculated from the fault model ranged between 10^{-9} and 10^{-10} at most of the observation stations. These changes were therefore considered to be groundwater changes caused by the ground shaking because groundwater level sensitivity to crustal volumetric strain is a few centimeters to 10^{-8} strain at the most. We compared the coseismic groundwater level changes for the Noto Hanto Earthquake with those for five recent large earthquakes and obtained rough characteristics of the effect of the ground shaking on the groundwater level at each of the observation stations.

Key words: Groundwater level, strain, coseismic change, oscillation, Noto Hanto Earthquake in 2007.

1. Introduction

Earthquake-related groundwater level changes have been reported repeatedly (Wakita, 1975; Roeloffs, 1988, 1996; Koizumi *et al.*, 1996). Quantitative evaluations of the relationship between the groundwater level and crustal static strain changes associated with earthquakes have been performed in recent years (Igarashi and Wakita, 1991; Quilty and Roeloffs, 1997; Koizumi *et al.*, 2004). Akita and Matsumoto (2004) investigated coseismic groundwater level changes in a great many observation wells in Hokkaido, Japan induced by five earthquakes with $M > 7.5$ that occurred around the Hokkaido region. These researchers showed that groundwater level changes could generally be explained by coseismic static volumetric strain changes. However, coseismic static strain changes have not been able to explain earthquake-related groundwater level changes on all occasions (Rojstaczer *et al.*, 1995; Koizumi *et al.*, 1996; Lai *et al.*, 2004).

As was reported by Montgomery and Manga (2003), ground shaking, which involves dynamic strain changes, in addition to coseismic strain changes, is also a causal main factor of earthquake-related groundwater level changes. Ground shaking causes consolidation, fracturing, fracture clearing or permeability enhancement (Brodsky *et al.*, 2003) and liquefaction, all of which subsequently induce groundwater level changes. Therefore, the effect of ground shaking is considered to greatly depend on geological structures as well as on the amplitudes and frequencies of the ground shaking (Lai *et al.*, 2004). Coseismic static strain changes generally attenuate in proportion to the cube of the hypocentral distance. In contrast, amplitudes of ground shaking attenuate in proportion to the hypocentral distance in the case of a body wave or to the route of the epicentral distance in the case of a surface wave. Therefore, as the hypocentral or epicentral distance is larger, the effect of ground shaking on groundwater level changes becomes larger than that of coseismic static strain changes. In actual fact, the sensitivity of groundwater level to crustal volumetric strain is a few centimeters to 10^{-8} strain at most (Roeloffs, 1996; Kitagawa *et al.*, 2004). It is therefore important to evaluate the effect of ground shaking on the groundwater level in the area where there are some coseismic and/or postseismic groundwater level changes but also where estimated coseismic static strain changes are smaller than 10^{-8}. A reasonable estimate of the effect of ground shaking can provide useful information for long-term evaluation of the stability of groundwater in the area.

The Noto Hanto Earthquake in 2007 occurred at the northwestern part of the Noto Hanto, Japan on March 25, 2007. This earthquake has an $M_{\rm JMA} = 6.9$, and the epicentral distances to almost all of our observation stations are 200–300 km. The coseismic static volumetric strain changes expected by the fault model of the earthquake (Awata *et al.*, 2007) is very small or ranges between 10^{-9}

and 10^{-10} at most of our groundwater observation stations. In contrast, the seismic intensity of each station was two to three on the scale of the Japan Meteorological Agency. Since the sensitivity of the groundwater level to volumetric strain change is a few centimeters to 10^{-8} strain at most, groundwater level changes caused by these small volumetric strain changes are expected to be 1 mm or smaller at most of the observation stations. Therefore it seems important to consider the effects of ground shaking in this case.

Here, we show groundwater changes related to the Noto Hanto Earthquake in 2007 and evaluate the effects of ground shaking on the groundwater level. We will compare the results with those of the other recent large earthquakes and try to determine the characteristics of the effects. In the following discussion, "coseismic strain changes" means "coseismic static strain changes".

2. Observation and Method

The Geological Survey of Japan (GSJ), AIST, has been monitoring groundwater as a means for predicting earthquakes since 1976. The groundwater observation network of GSJ currently comprises 42 stations in and around the Tokai and Kinki areas. At each station, groundwater level in an open well or pressure in a sealed well is observed as pore water pressure in the aquifer. For convenience, in this paper, the data on the groundwater pressure are expressed in the same units as those of the groundwater level. The data at 37 of the 42 stations, where the instruments for the observation worked well before and after the Noto Hanto Earthquake, were used for this analysis. The positions of those 37 observation stations are shown in Fig. 1. The sampling interval of the observed data is 2 min at most of the stations or 10 min at the other stations. Some of the observation stations have more than one observation well. We judged that the coseismic groundwater level change occurred at such observation stations if one of the wells was subjected to the coseismic change.

The sensitivity of the groundwater level to crustal volumetric strain is presumed by the tidal response of the groundwater level. Tidal components were extracted from the groundwater level data for 3 months before the Noto Hanto Earthquake using the BAYTAP-G program (Tamura *et al.*, 1991). The amplitude of the tidal volumetric strain at each observation station, which includes the components of the earth and oceanic tides, was calculated using the GOTIC2 program (Matsumoto *et al.*, 2001). The groundwater level sensitivity at each observation station was determined from these estimated tidal components (Table 1). We used the fault model of Awata *et al.* (2007) to calculate the coseismic volumetric strain changes caused by the Noto Hanto Earthquake in 2007. The length and width of the fault model are 15 and 12 km, respectively. The upper and western end is situated at 136.61E, 37.23E; the depth of the upper end is 2.0 km, the depth of lower end is 12.4 km, the strike is 58°, the dip is 60°, the rake is 117°, and the slip amount is 1.2 m, which is equal to the earthquake of M_w 6.5. Using this model, we calculated the coseismic volumetric strain change at each station using the program of Okada (1992). The theoretical coseismic groundwater level change was then calculated from the strain sensitivity and coseismic volumetric strain change at each station and compared with the observed change (Table 1).

Similar analyses were carried out for the 2004 Off Kii-Peninsula Earthquakes (foreshock and mainshock) (Geographical Survey Institute, 2004; Sato *et al.*, 2005), the 2003 Tokachi-oki Earthquake (Geographical Survey Institute, 2003; Sato *et al.*, 2004), the 2001 Geiyo Earthquake

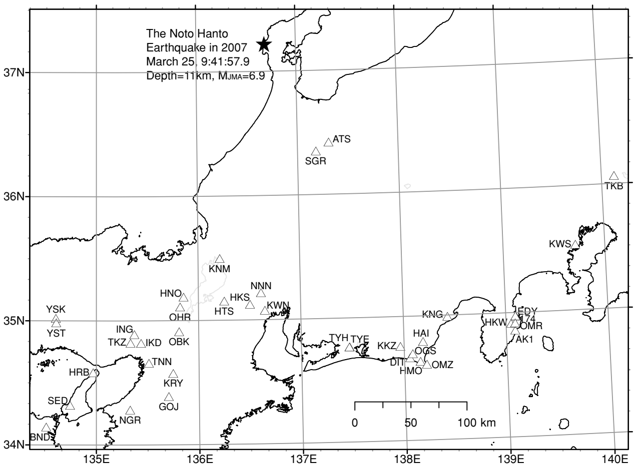

Fig. 1. Location of the groundwater observation stations of Geological Survey of Japan, AIST (triangle mark) and the epicenter of the Noto Hanto Earthquake in 2007 (star mark).

Table 1. Groundwater level sensitivity to volumetric strain and expected groundwater level change from the coseismic volumetric strain change.

Stn.	Location [deg]		Observed WL(*1) [mm]		Theoritical tidal VS(*1) amplitude [E-09]		Sensitivity [mm / E-09]	Coseismic VS change [E-09]	Noto Hanto Earthquake in 2007: Epicentral distance [km]	Expected WL change [mm]	Type of coseismic WL change(*3)				
	Lat.	Long.	O1(*2)	M2(*2)	O1	M2					S	T	I	D	O
174	34.97	139.10	30.8	58.3	2.4	6.8	8.62	1.04	331	-9.0					x
AK1	34.86	139.09	1.1	2.0	2.3	6.6	0.30	0.94	340	-0.3					
ATS	36.42	137.31	0.2	0.3	6.7	10.0	0.03	22.04	105	-0.8		x	x		
BND	34.14	134.51	6.2	10.5	4.3	9.1	1.15	-0.32	394	0.4					
DIT	34.67	138.06	2.7	7.9	2.2	3.1	2.52	0.82	309	-2.1					x
EDY	34.97	139.09	25.9	45.1	3.7	11.1	4.07	1.05	331	-4.3					x
GOJ	34.39	135.70	6.0	7.8	6.1	9.2	0.85	-0.39	326	0.3					
HAI	34.79	138.18	1.4	1.6	5.5	8.4	0.19	0.99	301	-0.2		x	x		
HKS	35.13	136.50	0.2	0.1	6.5	10.3	0.01	-0.38	233	0.0					x
HKW	34.91	139.05	0.0	0.0	4.5	7.6	0.00	1.01	333	0.0					
HMO	34.63	138.16	0.1	0.5	1.7	6.0	0.08	0.80	316	-0.1		x		x	x
HNO	35.19	135.85	104.2	27.7	6.3	9.6	2.88	-1.16	237	3.3		x		x	x
HRB	34.58	134.97	23.4	15.6	20.7	21.1	0.74	-0.52	331	0.4					x
HTS	35.15	136.25	0.0	0.0	6.3	9.6	0.00	-0.77	232	0.0		x	x		x
IKD	34.82	135.44	2.5	2.1	6.3	9.5	0.22	-0.72	289	0.2		x	x		x
ING	34.89	135.37	0.6	0.5	6.5	9.8	0.05	-0.79	284	0.0		x	x		x
KKZ	34.76	137.96	0.0	0.1	6.1	9.5	0.01	0.90	296	0.0		x		x	x
KNG	34.99	138.43	0.5	1.0	3.0	3.2	0.32	1.26	293	-0.4		x		x	x
KNM	35.50	136.21	8.7	12.5	6.4	9.7	1.29	-1.62	196	2.1	x		x		
KRY	34.58	135.75	10.1	14.7	6.1	9.3	1.58	-0.49	305	0.8					x
KWN	35.08	136.65	0.8	1.6	3.3	1.9	0.87	-0.13	238	0.1					x
KWS	35.53	139.71	4.1	4.1	2.7	6.2	0.67	1.16	330	-0.8		x		x	
NNN	35.22	136.61	16.6	55.6	6.4	10.1	5.51	-0.26	222	1.4					
OBK	34.91	135.81	7.6	12.1	6.2	9.4	1.28	-0.76	268	1.0					x
OGS	34.70	138.08	0.3	0.2	4.1	5.2	0.04	0.86	307	0.0					x
OHR	35.11	135.82	7.8	13.9	6.3	9.6	1.46	-1.03	247	1.5		x		x	x
OMR	34.92	139.09	2.0	2.8	2.8	6.3	0.45	1.00	335	-0.4		x		x	
OMZ	34.61	138.22	0.3	0.2	10.8	29.7	0.01	0.79	321	0.0					x
SED	34.32	134.75	6.7	6.5	2.4	11.9	0.55	-0.39	366	0.2					x
SGR	36.35	137.18	5.2	2.5	6.7	10.0	0.25	15.96	106	-4.0					
TKB	36.06	140.12	2.0	2.9	6.0	9.6	0.31	1.06	334	-0.3	x		x		
TKZ	34.82	135.33	12.9	19.1	6.1	9.3	2.06	-0.72	293	1.5					x
TNN	34.66	135.51	2.8	3.6	5.0	7.9	0.45	-0.58	303	0.3					x
TYE	34.77	137.47	0.0	0.0	5.9	8.9	0.00	0.66	281	0.0					
TYH	34.77	137.47	4.4	2.9	5.9	8.8	0.33	0.65	281	-0.2		x		x	
YSK	35.02	134.60	20.8	44.8	6.6	9.6	4.66	-0.67	307	3.1					x
YST	34.99	134.61	8.5	14.9	6.7	9.5	1.57	-0.65	310	1.0	x		x		x

(*1) WL and VS mean water level and volumetric strain, respectively. (*2) O1 and M2 denote tidal components. The period of O1 and M2 is 25.8 hours and 12.4 hours, respectively. (*3) S: Step like change, T: Trend change, I: Increase, D: Decrease, O: Oscillation.

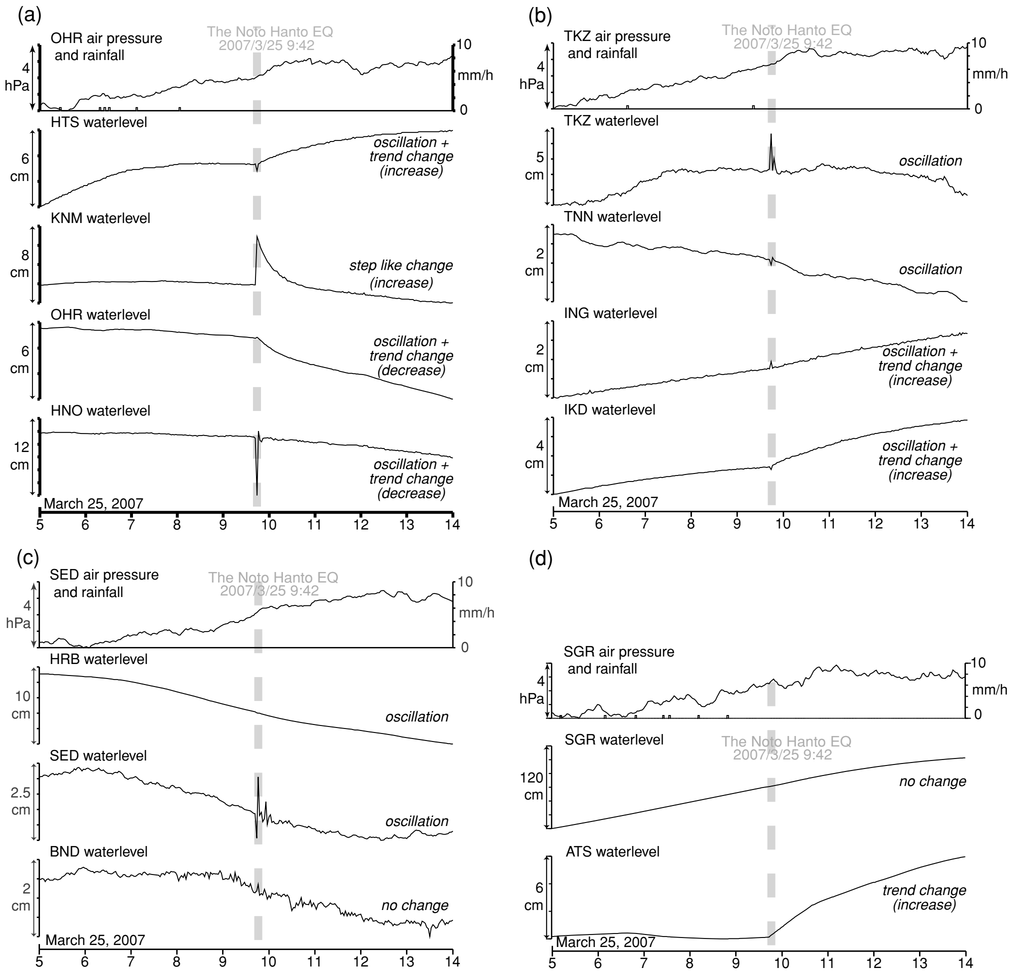

Fig. 2. (a) Observed water level changes at HTS, KNM, OHR and HNO before and after the Noto Hanto Earthquake. The sampling interval is 2 min. (b) Observed water level changes at TKZ, TNN, ING and IKD. (c) Observed water level changes at HRB, SED, and BND. (d) Observed water level changes at SGR and ATS.

(Geographical Survey Institute, 2001; Koizumi *et al.*, 2002) and the Western Tottori Earthquake in 2000 (Geographical Survey Institute, 2000; Takahashi *et al.*, 2002). The results of these analyses were compared with those of the Noto Hanto Earthquake.

3. Results

At many of our observation stations, we detected coseismic and/or postseismic groundwater level changes related to the Noto Hanto Earthquake. Most of these were short-term oscillations and/or changes in the trend. Typical examples of the observed groundwater level changes are shown in Figs. 2(a) to 2(d). Those graphs show 2-min values. Oscillations in the groundwater level occurred at HTS, HNO, TKZ, TNN, ING, IKD and SED. There are several possible factors that could explain why the patterns of the oscillations in the groundwater levels are different: (1) the ground shaking was different at the different stations; (2) aliasing probably occurred because the sampling interval (2 min) is generally longer than the period of the oscillation; (3) there possibly occurred a kind of resonance so that the oscillation at a certain period, which depends on the geometrical structure of the well, is amplified (Cooper *et al.*, 1965; Kunugi *et al.*, 2000). Resonance is considered to have occurred at SED in particular, where the oscillation continued for longer time than at the other stations. At KNM, there was a step-like change in the groundwater level. However, such step-like coseismic changes were observed only at three stations (KNM, TKB, and YST); at the other 13 stations, there were changes in the trend of the groundwater level (Table 1).

It is difficult to evaluate the oscillations of the groundwater level because aliasing probably occurred. The step-like coseismic changes were easy to quantitatively evaluate, but were only observed at the three stations mentioned above. Therefore, we principally evaluated the 13 coseismic changes in the trend of the groundwater level, although quantitative evaluation of the trend changes was usually difficult. Ultimately, we were able to estimate the amount of coseismic water level change only at five stations (KNM, TKB, YST, ATS and HTS).

4. Discussion

As mentioned above, we were unable to estimate the amplitudes of the changes in the long-term trend for many stations. However their final amplitudes were at the very least larger than a few millimeters. The coseismic volumetric strain changes were calculated at the observation stations

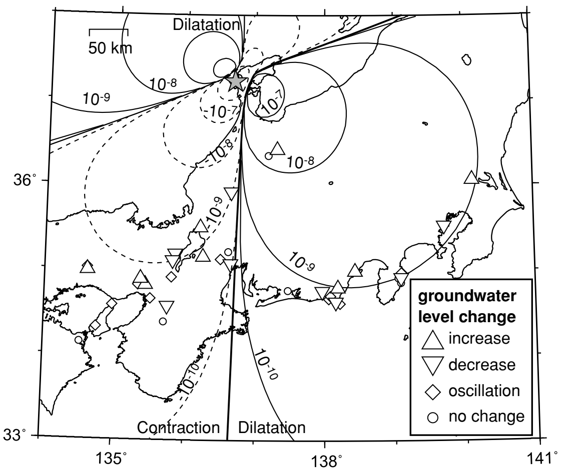

Fig. 3. Coseismic groundwater level changes in response to the Noto Hanto Earthquake in 2007. Contours denote the coseismic volumetric strain changes calculated from the fault model of Awata *et al*. (2007).

using the fault model of Awata *et al.* (2007). Most of these changes range between 10^{-9} and 10^{-10} (Table 1; Fig. 3). Therefore coseismic groundwater level changes expected from those volumetric strain changes are smaller than 1 mm at most of the stations where the coseismic trend changes were observed (Table 1). This suggests that those trend changes were not caused by the volumetric strain changes but by the ground shaking. According to Montgomery and Manga (2003), ground shaking can cause consolidation, fracturing, and fracture cleaning of the ground. Consolidation seems also to cause permeability to decrease, while fracturing or/and fracture cleaning can cause it to increase. When such permeability changes occur, it is assumed that pressure distribution in the aquifer will shift to a new equilibrium situation. Since the movement of groundwater usually takes much time, the groundwater pressure at a certain point changes gradually, which is considered to be the cause of the many long-term trend changes that were observed.

At the five stations where the amount of coseismic water level changes were estimated, we investigated the relation among the epicentral distances, calculated coseismic volumetric strain changes and coseismic groundwater level changes expected from those volumetric strain changes and observed coseismic water level changes (Fig. 4). Figure 4 shows a kind of linear relation between the epicentral distances and observed water level changes although both the volumetric strain changes and expected groundwater level changes have no relation to observed groundwater level changes. In general, if the coseismic change is caused by the strain change, it decreases in inverse proportion to the cube of the hypocentral distance, which is almost equal to the epicentral distance in the far-field area in the case of a shallow earthquake, such as the Noto Hanto Earthquake in 2007. In contrast, if the coseismic change is caused by ground shaking, it decreases in inverse proportion to the hypocentral distance for the body wave or to the route of the epicentral distance for the surface wave. These results in Fig. 4 also suggest that the water level changes were caused by ground shaking.

In order to clarify the effect of ground shaking on the

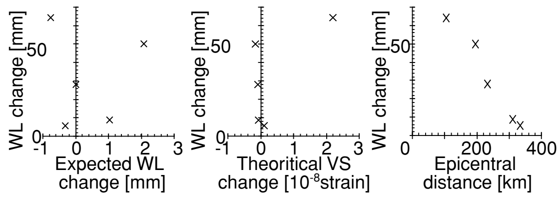

Fig. 4. Relation among the epicentral distances, theoretical volumetric strain changes calculated from the fault model of Awata *et al*. (2007), coseismic water level changes expected from the volumetric strain changes and observed water level changes at the five stations (ATS, HTS, KNM, TKB and YST) where the amount of coseismic water level change was estimated. *WL and VS mean water level, and volumetric strain change, respectively.

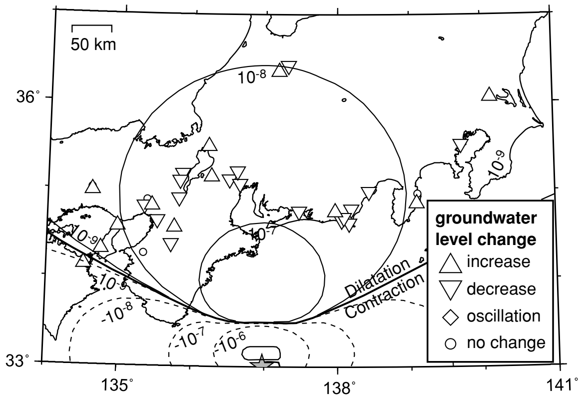

Fig. 5. Coseismic groundwater level change in response to the foreshock of the 2004 Off Kii-Peninsula Earthquakes (Sato *et al*., 2005). Contours denote the coseismic volumetric strain changes calculated from the fault model of the Geographical Survey Institute (2004).

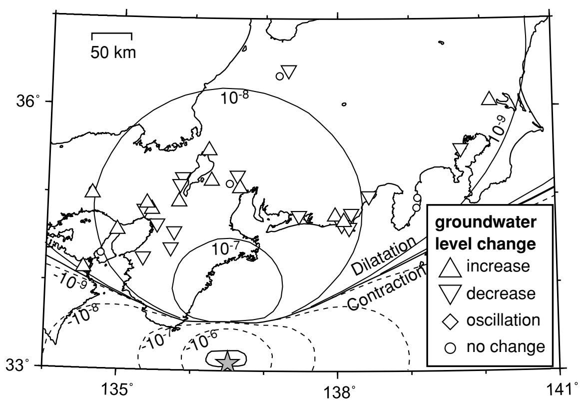

Fig. 6. Coseismic groundwater level changes in response to the mainshock of the 2004 Off Kii-Peninsula Earthquakes (Sato *et al*., 2005). Contours denote the coseismic volumetric strain changes calculated from the fault model of the Geographical Survey Institute (2004).

groundwater level at each observation station, we compared the coseismic groundwater level changes for Noto Hanto Earthquake with those for the recent large earthquakes. These are shown in Table 2 and in Figs. 5–9. The earthquakes shown are the foreshock and main shock of the 2004 Off Kii-Peninsula Earthquakes (Figs. 5 and 6, respectively), the 2003 Tokachi-Oki Earthquake (Fig. 7), the 2001 Geiyo Earthquake (Fig. 8) and the Western Tottori Earthquake in 2000 (Fig. 9). In the following discussion we did not con-

Table 2. Observed coseismic groundwater level change and calculated volumetric strain change in response to five recent large earthquakes. For WL, I, D and O, refer to the caption of Table 1. For a–e in the column of classification, refer to the text.

Stn.	2007 Noto Hanto		2004 Off Kii-Pen. (mainshock)		2004 Off Kii-Pen. (foreshock)		2003 Tokachi-oki		2001 Geiyo		2000 Western Tottori		number of under 10^{-8} (VS)	number of I or D	classification
	Type of WL change	Strain change [E-09]	Type of WL change	Strain change [E-09]	Type of WL change	Strain change [E-09]	Type of WL change	Strain change [E-09]	Type of WL change	Strain change [E-09]	Type of WL change	Strain change [E-09]			
174	O	1.04	N	8.08	N	3.29	O	-1.85	-	-	N	0.42	5	0	e
AK1	N(*1)	0.94	I	8.01	N	3.03	-	-	-	-	N	0.44	4	1	e
ATS	***I(*2)***	***22.03***	D	9.91	D	7.43	N	-2.22	-	-	N	0.30	4	2	a
BND	N	-0.32	I	-1.30	I	1.61	O	-0.78	I	-5.93	O	7.08	6	3	a
DIT	O	0.82	***D***	***40.86***	***D***	***16.22***	N	-1.56	-	-	O	0.82	3	0	e
EDY	O	1.05	- (*3)	-	-	-	-	-	-	-	-	-	1	0	e
GOJ	N	-0.39	***D***	***35.78***	***D***	***65.00***	N	-1.04	O	-2.12	D	5.26	4	1	e
HAI	I	0.98	***D***	***30.86***	***D***	***12.95***	N	-1.65	-	-	D	0.75	3	2	d
HKS	O	-0.38	***D***	***40.32***	***N***	***35.88***	N	-1.40	O	-1.08	D	2.58	4	1	e
HKW	N	1.01	-	-	-	-	N	-1.80	-	-	N	0.44	3	0	e
HMO	D	0.80	***D***	***36.23***	***D***	***13.70***	N	-1.56	-	-	O	0.77	3	1	e
HNO	D	-1.16	***D***	***24.30***	***D***	***27.26***	O	-1.23	O	-1.65	D	5.06	4	2	a
HRB	O	-0.52	***I***	8.63	***I***	***16.70***	N	-0.92	D	-4.11	***D***	***14.57***	4	2	d
HTS	I	-0.77	***I***	***34.01***	***I***	***33.43***	N	-1.34	I	-1.27	I	3.28	4	3	a
IKD	I	-0.72	***I***	***19.81***	***I***	***29.14***	N	-1.05	I	-2.57	I	9.23	4	3	a
ING	I	-0.79	***N***	***17.59***	***I***	***25.37***	N	-1.05	I	-2.65	***I***	***10.28***	3	2	a
KKZ	D	0.90	***I***	***42.01***	***I***	***18.22***	-	-	-	-	I	0.86	2	2	d
KNG	D	1.26	***D***	***19.80***	D	8.86	D	-1.80	-	-	D	0.62	4	4	a
KNM	I	-1.62	***I***	***22.35***	***I***	***21.24***	I	-1.41	I	-1.15	I	2.67	4	4	a
KRY	O	-0.49	***I***	***35.95***	***D***	***55.00***	-	-	I	-2.05	D	5.67	3	2	c
KWN	O	-0.13	***D***	***45.68***	***I***	***38.19***	I	-1.43	O	-0.99	I	2.29	4	2	a
KWS	D	1.16	***D***	3.93	D	1.93	D	-2.34	-	-	N	0.27	5	4	a
NGR	-	-	***N***	***14.05***	***D***	***34.18***	N	-0.95	O	-2.91	D	6.72	4	1	e
NNN	N	-0.26	***D***	***36.99***	***D***	***31.33***	N	-1.46	O	-0.98	D	2.23	4	1	e
OBK	O	-0.76	***D***	***30.10***	***(*4)***	***37.60***	I	-1.16	I	-1.86	D	5.77	4	3	(*5)
OGS	O	0.86	***D***	***38.29***	***I***	***15.45***	N	-1.58	-	-	D	0.80	3	1	e
OHR	D	-1.03	***D***	***25.38***	***D***	***29.45***	D	-1.20	D	-1.74	D	5.47	4	4	a
OMR	D	1.00	-	-	-	-	N	-1.81	-	-	N	0.43	3	1	e
OMZ	O	0.79	-	-	-	-	N	-1.55	-	-	O	0.74	3	0	e
SED	O	-0.39	***I***	2.60	N	8.62	N	-0.84	I	-5.11	***D***	***11.36***	5	2	a
SGR	***N***	***15.96***	***I***	***10.69***	N	8.14	N	-2.11	-	-	N	0.36	3	0	e
TKB	I	1.06	***I***	2.62	(*4)	1.44	I	-3.00	-	-	N	0.17	5	4	(*6)
TKZ	O	-0.72	***D***	***17.05***	***D***	***25.75***	O	-1.03	I	-2.80	***D***	***10.65***	3	1	e
TNN	O	-0.58	***D***	***23.58***	***D***	***37.30***	I	-1.05	D	-2.49	D	7.80	4	3	d
TYE	N	0.66	-	-	-	-	-	-	-	-	-	-	1	0	e
TYH	D	0.65	***D***	***66.85***	***D***	***34.88***	N	-1.51	-	-	D	1.22	3	2	b
YSK	O	-0.67	N	5.89	N	9.13	O	-0.88	I	-4.50	***O***	***42.18***	5	1	e
YST	I	-0.65	I	5.85	I	9.23	O	-0.87	-	-	***D***	***41.15***	4	3	a

(*1) N means no detection of the coseismic groundwater level change. (*2) Characters or numbers in ***bold italic***s show that coseismic volumetric strain change is 10^{-8} or greater. (*3) "-" means there was no observed data. (*4) The results at two wells at the same observation station were different. (*5) c at OBK1, d at OBK2. (*6) a at TKB3, d at TKB4.

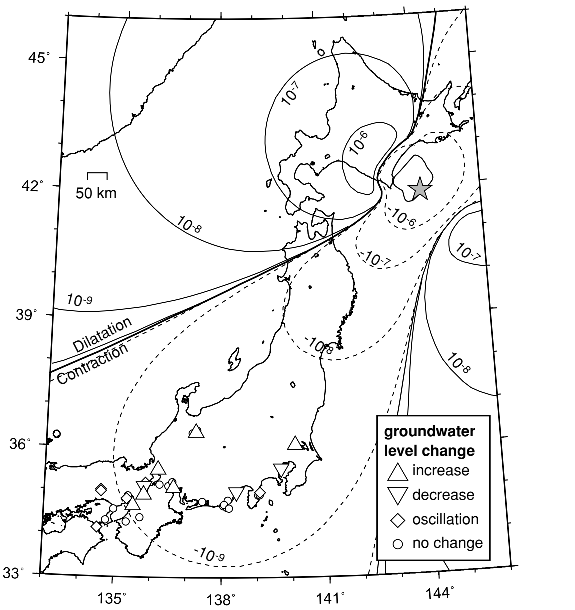

Fig. 7. Coseismic groundwater level changes in response to the 2003 Tokachi-Oki Earthquake (Akita and Matsumoto, 2004; Sato *et al.*, 2004). Contours denote the coseismic volumetric strain changes calculated from the fault model of the Geographical Survey Institute (2003).

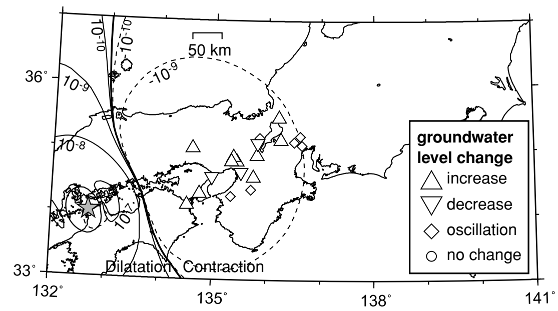

Fig. 8. Coseismic groundwater level changes in response to the 2001 Geiyo Earthquake (Koizumi *et al.*, 2002). Contours denote the coseismic volumetric strain changes calculated from the fault model of the Geographical Survey Institute (2001).

sider the results at the groundwater stations where there were no or only one coseismic change related to those earthquakes. We also focused our attention on those groundwater level changes at the observation stations where estimated coseismic volumetric strain changes were smaller than 10^{-8}. We found five groups of observation stations:

(a) ones in which the direction (rise or drop) of the water level changes was constant and inconsistent with that of the coseismic volumetric strain changes at the station;
(b) ones in which the direction of the water level changes was constant and consistent with that of coseismic volumetric strain changes;
(c) ones in which the direction of the water level changes was variable and consistent with that of the coseismic volumetric strain changes;
(d) ones in which the direction of the water level changes was variable and inconsistent with that of the coseismic volumetric strain changes;

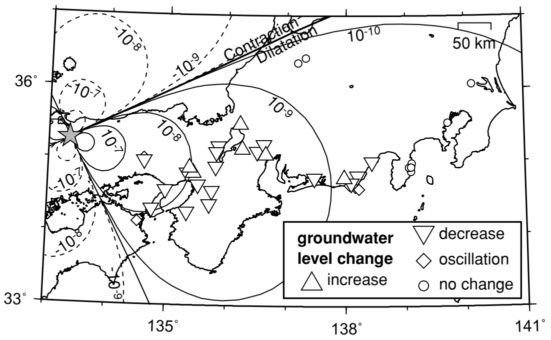

Fig. 9. Coseismic groundwater level changes in response to the Western Tottori Earthquake in 2000 (Takahashi *et al.*, 2002). Contours denote the coseismic volumetric strain changes calculated from the fault model of the Geographical Survey Institute (2000).

Table 3. Classification of the stations based on the pattern of the coseismic changes.

Class	Num.	Station					
a	14	ATS	BND	HNO	HTS	IKD	ING
		KNG	KNM	KWN	KWS	OHR	SED
		YST	TKB3				
b	1	TYH					
c	2	KRY	OBK1				
d	6	HAI	HRB	KKZ	OBK2	TNN	TKB4
e	17	174	AK1	DIT	EDY	GOJ	HKS
		HKW	HMO	NGR	NNN	OGS	OMR
		OMZ	SGR	TKZ	TYE	YSK	

(e) the other stations, which include those stations where there was no or only one coseismic groundwater level change (Tables 2 and 3).

We consider that consolidation, fracturing, fracture clearing or liquefaction could easily have been caused by ground shaking at stations belonging to categories (a) and (d). Those stations that belong to category (c) might be sensitive to the coseismic volumetric strain changes. However there are few of such stations. Based on our results, we are unable to make an assessment of the stations belonging to groups (b) and (e) (Table 3).

We have determined the rough characteristics of the effect of ground shaking on the groundwater level. In order to obtain more details on these characteristics and to clarify the mechanisms which produce the effect at each of the stations, we need the observation records of coseismic groundwater levels whose sampling interval is much shorter than 2 min. The effect of ground shaking is conspicuous in the groundwater oscillation and because of this, an understanding of groundwater oscillations is important to our understanding of the mechanism of earthquake-related groundwater changes. We are now ready for a high-sampling groundwater level observation system.

5. Conclusions

There were many coseismic and/or postseismic groundwater level changes related to the Noto Hanto Earthquake in 2007 at the groundwater observation stations of the Geological Survey of Japan, AIST. At the five stations where the amount of coseismic water level change was estimated in this study, a kind of linear relation is recognized between the epicentral distance and the observed coseismic water level change for the Noto Hanto Earthquake in 2007. The estimated coseismic volumetric strain changes are smaller than 10^{-8} at most of the observation stations. Therefore, it is considered that most of observed groundwater level changes in the Noto Hanto Earthquake in 2007 were caused by ground shaking. We compared the coseismic groundwater level changes for Noto Hanto Earthquake with those for five recent large earthquakes and determined the rough characteristics of the effect of the ground shaking on the groundwater level at each of the observation stations.

Acknowledgments. We thank Dr. Tsukuda and an anonymous reviewer for valuable comments to improve this paper. We are grateful to the many people who have helped us with our groundwater observations.

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S. Itaba (e-mail: itaba-s@aist.go.jp), N. Koizumi, N. Matsumoto, M. Takahashi, T. Sato, R. Ohtani, Y. Kitagawa, Y. Kuwahara, T. Sato, and K. Ozawa