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Groundwater changes associated with the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes

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The Geological Survey of Japan, AIST, has been monitoring groundwater in and around the Kinki and Tokai districts for earthquake prediction research. The Niigata Prefectural Office has also been observing groundwater for monitoring land subsidence in Niigata Prefecture. The 2004 Niigata-Chuetsu (M_{JMA} 6.8) and 2007 Chuetsu-oki (M_{JMA} 6.8) earthquakes occurred in Niigata Prefecture, Japan, on October 23, 2004 and July 16, 2007, respectively. The two earthquakes have a similar magnitude, epicenter, and mechanism. At many of the observation wells, we detected changes in groundwater level or pressure related to the two earthquakes, but no clear precursory changes. At all of our observation wells in Niigata Prefecture, trend changes were observed after coseismic step-like changes for both of the earthquakes. At some of the stations in and around the Kinki and Tokai districts, coseismic trend changes and/or step-like changes were observed. The pattern of the changes were almost similar for the two earthquakes. Those changes were considered to be caused not by the static crustal deformation but by the ground shaking.

Key words: Groundwater, strain, coseismic change, ground shaking, 2007 Chuetsu-oki earthquake, 2004 Niigata-Chuetsu earthquake, long-term stability of groundwater.

1. Introduction

Earthquakes cause ground shaking and static crustal deformation. Therefore, earthquake-related groundwater changes are considered to be caused by the ground shaking and static crustal deformation. According to the poroelastic theory (Biot, 1941; Roeloffs, 1996), stress, strain, pore pressure, and water content are related to each other. On the basis of this knowledge, Montgomery and Manga (2003) pointed out that there are two main factors for earthquake-related groundwater change. One is the static volumetric strain change and the other is ground shaking, which includes the dynamic volumetric strain change. In addition, static earthquake-related displacement of the crust, especially the vertical displacement, can also have some effect on groundwater. However, the amplitude of the ground motion decreases in inverse proportion to the hypocentral distance for the body wave or route of the epicentral distance for surface wave, while the amplitude of static volumetric strain change and static displacement, respectively, decreases in inverse proportion to the cubic and square of the hypocentral distance. Therefore, in the neighborhood of the focal region, we have to consider the effects of both static crustal deformation and ground shaking. However, in the area far enough from the focal region, the effect of static crustal deformation is much smaller than that of the ground shaking and can be neglected. For unconfined groundwater, whose strain sensitivity is very low (Bredehoeft, 1967), the effect of the volumetric strain changes can usually be neglected.

For any evaluation of the long-term stability of groundwater in Japan, it is important to investigate earthquake-related changes, their recoveries, and reproducibility. The magnitude, hypocenter, and mechanism of the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes are almost the same, although they are large and disastrous earthquakes. Therefore, distributions of the seismic intensities and coseismic static crustal deformation of the two earthquakes are large and similar, and they occurred within a few years of each other. It is a very rare case. Therefore, it seems meaningful to investigate the earthquake-related groundwater changes for the two earthquakes, even though only two cases are not enough to check the reproducibility. In this paper, we will discuss the earthquake-related groundwater level (or pressure) changes and their recoveries based on the groundwater level data in Niigata Prefecture or in the neighborhood of the focal region and those in and around the Tokai and Kinki districts, which are far from the focal region.

2. Observation

Since Niigata Prefecture produces oil and natural gas, many boring tests have been performed. Those tests show that high-pressure thermal water, whose pressure is shifted

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Table 1. The location of the observation wells, the tidal amplitude of observed water level (or pressure) and theoretical tidal volumetric strain change, groundwater level sensitivity to volumetric strain, calculated coseismic volumetric strain change, expected coseismic ground water level change from the coseismic strain change, and the type of observed water level (or pressure) change.

well name	Location [deg]		Observed WL(*1) [mm]		Theoritical tidal VS(*1) amplitude [E-09]		Sensitivity [mm / E-09](*3)	2004 Mid-Niigata Prefecture							2007 Niigataken-Chuetsuoki							Geology (*6)
								Coseismic VS change [E-09]	Expected WL change [mm]	Epicentral distance [km]	SI (*4)	Type of coseismic WL change (*5)			Coseismic VS change [E-09]	Expected WL change [mm]	Epicentral distance [km]	SI	Type of coseismic WL change			
	Lat.	Long.	O1(*2)	M2(*2)	O1	M2						S	T	O					S	T	O	
JO4	37.16	138.25	0.02	0.06	7.7	10.4	0.00	67.1	0.0	56	5-	v	^	?	-208.3	0.0	54	5+	v	^	?	Qs
JO3	37.16	138.25	0.02	0.03	7.7	10.4	0.00	67.1	0.0	56	5-	v	^	?	-208.3	0.0	54	5+	v	^	?	Qs
KB4	37.21	138.30	0.03	0.02	8.0	10.5	0.00	116.4	0.0	51	5-	^	^	?	-375.7	0.0	47	5+	^	^	?	Qs
KB3	37.21	138.30	0.04	0.06	8.0	10.5	0.00	116.4	0.0	51	5-	v	^	?	-375.7	0.0	47	5+	v	^	?	Qs
TK4	37.14	138.31	0.03	0.07	7.1	10.1	0.00	41.9	0.0	52	5-	v	^	?	-175.8	0.0	53	5+	v	^	?	Qs
TK2	37.12	138.25	0.02	0.05	7.2	10.1	0.00	40.3	0.0	58	5-	v	^	?	-155.4	0.0	58	5+	v	^	?	Qs
SK4	37.18	138.29	0.00	0.03	7.7	10.4	0.00	85.1	0.0	53	5-	v	^	?	-271.6	0.0	51	5+	v	^	?	Qs
K52	37.11	138.25	0.01	0.01	7.0	10.1	0.00	30.3	0.0	59	5-	v	^	?	-137.9	0.0	59	5+	v	^	?	Qs
HGS	37.45	138.80	0.09	0.04	6.7	10.0	0.00	-5376.0	0.0	19	6-	v	^	?	102.8	0.0	20	5-	v		?	Qs
AK1	34.86	139.09	1.15	1.96	2.3	6.6	0.40	0.3	-0.1	271	1				0.5	-0.2	303	1				Tv
ATS	36.42	137.31	0.17	0.34	6.7	10.0	0.03	-0.8	0.0	169	2		^	o	-3.1	0.1	171	2		^	o	PTs
BND	34.14	134.51	6.21	10.47	4.3	9.1	1.30	-0.1	0.1	526				o	-0.1	0.1	529			v	o	Qs
DIT	34.67	138.06	2.69	7.88	2.2	3.1	1.89	-0.5	1.0	301	1			o	-0.3	0.5	325	2			o	Qs
EDY	34.97	139.09	25.89	45.10	3.7	11.1	5.56	-	-	-	1	-	-	-	0.6	-3.5	290	1	v		o	Tv
GOJ	34.39	135.70	5.99	7.76	6.1	9.2	0.92	-0.2	0.2	431					-0.2	0.2	438				o	PTv
GOT	35.82	137.55	11.11	11.74	6.4	9.7	1.47	-2.4	3.5	201	1			o	-2.1	3.2	214	2	v			PTs
HAI	34.79	138.18	1.38	1.58	5.5	8.4	0.22	-0.6	0.1	284	1			o	-0.2	0.1	309	1			o	Ts
HGM1	33.87	135.73	17.60	26.87	6.0	9.6	2.86	-	-	-	-	-	-	-	-0.2	0.5	485		v		o	Ts
HGM2	33.87	135.73	13.53	20.30	6.0	9.6	2.18	-	-	-	-	-	-	-	-0.2	0.4	485		v		o	Ts
HGM3	33.87	135.73	0.19	0.12	6.0	9.6	0.02	-	-	-	-	-	-	-	-0.2	0.0	485				o	Ts
HKSi	35.13	136.50	0.58	0.58	6.5	10.3	0.07	-0.5	0.0	321				o	-0.6	0.0	329				o	Qs
HKSo	35.13	136.50	0.10	0.08	6.5	10.3	0.00	-0.5	0.0	321				o	-0.6	0.0	329					Qs
HKW	34.91	139.05	0.02	0.01	4.5	7.6	0.00	0.3	0.0	265	1				0.5	0.0	296	1				Tv
HMO	34.63	138.16	0.48	0.50	1.7	6.0	0.19	-0.5	0.1	302	1			o	-0.2	0.0	327	2				Ts
HMO1	34.63	138.15	0.34	0.61	1.7	6.1	0.15	-0.5	0.1	303	1				-0.2	0.0	328	2	v		o	Ts
HMO2	34.63	138.15	0.05	0.03	1.7	6.1	0.00	-0.5	0.0	303	1		v	o	-0.2	0.0	328	2		v		Ts
HNO	35.19	135.85	10.19	10.19	6.3	9.6	1.34	-0.2	0.3	357				o	-0.3	0.4	361				o	PTs
HRB	34.58	134.97	23.37	15.64	20.7	21.1	0.94	-0.1	0.1	463					-0.1	0.1	465		v	v		PTv
HTS	35.15	136.25	0.00	0.00	6.3	9.6	0.00	-0.4	0.0	334			^	o	-0.5	0.0	340			^	o	Qs
ICU1	33.90	136.14	1.40	3.47	1.5	5.2	0.81	-	-	-	-	-	-	-	-0.2	0.2	463				o	Tv
ICU2	33.90	136.14	2.36	2.75	1.5	5.2	1.06	-	-	-	-	-	-	-	-0.2	0.2	463				o	Tv
ICU3	33.90	136.14	0.87	0.41	1.5	5.2	0.33	-	-	-	-	-	-	-	-0.2	0.1	463				o	Tv
IKD	34.82	135.44	2.47	2.08	6.3	9.5	0.31	-0.1	0.0	413	1		^	o	-0.2	0.1	417	1		^	o	Qs
IKH	34.51	134.90	18.49	11.01	2.8	9.7	3.87	-0.1	0.3	473					-	-	-	-	-	-	-	PTv
ING	34.89	135.37	0.61	0.48	6.5	9.8	0.07	-0.1	0.0	412	1		^	o	-	-	-	-	-	-	-	PTs
KKZ1	34.76	137.96	0.00	0.10	6.1	9.5	0.00	-0.6	0.0	293	2			o	-0.4	0.0	316	2		v	o	Ts
KKZ2	34.76	137.96	0.00	0.86	6.1	9.5	0.00	-0.6	0.0	293	2			o	-0.4	0.0	316	2		^		Ts
KNG1	34.99	138.43	2.11	4.43	3.0	3.2	1.06	-0.5	0.6	259	1			o	-0.1	0.1	285	1	v	v	o	Ts
KNG2	34.99	138.43	2.06	3.47	3.0	3.2	0.90	-0.5	0.5	259	1			o	-0.1	0.1	285	1	v	v	o	Qs
KNG3	34.99	138.43	0.40	0.11	3.0	3.2	0.08	-0.5	0.0	259	1			o	-0.1	0.0	285	1			o	Qs
KNM	35.50	136.21	8.70	12.46	6.4	9.7	1.32	-0.3	0.4	310			v	o	-0.5	0.6	313				o	Qs
KRY	34.58	135.75	10.13	14.74	6.1	9.3	1.62	-0.2	0.3	412					-0.2	0.4	419				o	PTv
KWNi	35.08	136.65	0.33	0.17	3.3	1.9	0.09	-0.6	0.1	317	2				-0.6	0.1	327	2			o	Qs
KWNo	35.08	136.65	0.61	1.56	3.3	1.9	0.51	-0.6	0.3	317	2	^			-0.6	0.3	327	2				Qs
KWS	35.53	139.71	4.12	4.14	2.7	6.2	1.10	3.6	-4.0	210	2	v		o	2.6	-2.9	246	2	v	v	o	Ts
NGR	34.28	135.33	0.07	0.04	6.1	9.6	0.00	-0.1	0.0	462	1				-0.2	0.0	469	1			o	Qs
NNN	35.22	136.61	16.60	55.64	6.4	10.1	4.04	-0.6	2.3	307	2				-0.6	2.6	315	2				Qs
OBK1	34.91	135.81	7.73	12.18	6.2	9.4	1.27	-0.2	0.3	382	1			o	-0.3	0.4	387	2	v		o	PTs
OBK2	34.91	135.81	7.73	6.13	6.2	9.4	0.95	-0.2	0.2	382	1		v		-	-	-	-	-	-	-	PTs
OGS	34.70	138.08	0.33	0.22	4.1	5.2	0.06	-0.6	0.0	297	1			o	-0.3	0.0	321	2			o	Qs
OHR	35.11	135.82	7.83	13.93	6.3	9.6	1.35	-0.2	0.3	366			v		-	-	-	-	-	-	-	PTv
OMR	34.92	139.09	2.05	2.84	2.8	6.3	0.59	0.4	-0.2	265	1	v			0.6	-0.3	296	1		^		Tv
OMZ	34.61	138.22	0.35	0.22	10.8	29.7	0.02	-0.4	0.0	304	1				-0.2	0.0	329	2				Ts
SED	34.32	134.75	6.70	6.49	2.4	11.9	1.64	-0.1	0.1	497				o	-0.1	0.2	500				o	Qs
SGR	36.35	137.18	5.17	2.52	6.7	10.0	0.51	-0.6	0.3	183	2		v		-2.3	1.2	185	2		v	o	PTs
TKB1	36.06	140.12	1.91	2.95	6.0	9.6	0.31	10.6	-3.3	177	3	v		o	5.7	-1.8	214	3	v	^	o	Qs
TKB2	36.06	140.12	1.07	1.71	6.0	9.6	0.18	10.6	-1.9	177	3	v		o	5.7	-1.0	214	3	^	^		Qs
TKB3	36.06	140.12	0.88	1.25	6.0	9.6	0.14	10.6	-1.5	177	3	v		o	5.7	-0.8	214	3	^	v		Qs
TKB4	36.06	140.12	0.60	0.72	6.0	9.6	0.09	10.6	-0.9	177	3	v	v	o	5.7	-0.5	214	3	^	v		Qs
TKZ	34.82	135.33	12.91	19.10	6.1	9.3	2.08	-0.1	0.2	420	1			o	-0.2	0.4	423	1			o	PTs
TNN	34.66	135.51	2.76	3.59	5.0	7.9	0.50	-0.2	0.1	421	1			o	-0.2	0.1	426	1		v		Qs
TYE	34.77	137.47	2.11	1.59	5.9	8.9	0.27	-0.7	0.2	307	2		v		-0.5	0.1	326	2				PTs
TYH1	34.77	137.47	4.84	3.93	5.9	8.8	0.63	-0.7	0.4	308	2		v		-0.5	0.3	326	2		v	o	PTs
TYH2	34.77	137.47	7.08	10.18	5.9	8.8	1.18	-0.7	0.8	308	2				-0.5	0.6	326	2		v	o	PTs
YSK	35.02	134.60	20.81	44.78	6.6	9.6	3.90	0.0	0.0	459				o	0.0	0.2	457				o	PTs
YST1	34.99	134.61	6.04	7.52	6.7	9.5	0.84	0.0	0.0	461		^		o	-0.1	0.0	459			^	o	PTs
YST2	34.99	134.61	8.47	16.10	6.7	9.5	1.48	0.0	0.0	461			^	o	-0.1	0.1	459			^	o	PTs
YST3	34.99	134.61	3.89	4.49	6.7	9.5	0.53	0.0	0.0	461			^	o	-0.1	0.0	459			^	o	PTs
174	34.97	139.10	30.75	58.32	2.4	6.8	10.75	0.4	-4.7	259	1			o	0.6	-6.8	291	1			o	Tv

(*1) WL and VS mean water level and volumetric strain, respectively. E-09 means 10^{-9} strain.

(*2) O1 and M2 denote tidal components. The period of O1 and M2 is 25.8 h and 12.4 h, respectively.

(*3) The average of the strain sensitivities for O1 and M2 components.

(*4) SI means the seismic intensity in the scale of the Japan Meteorological Agency. 5−, 5+ and 6− mean '5 lower', '5 upper' and '6 lower', respectively.

(*5) S+^ is step up, S+v is step down, T+^ is trend up and T+v is trend down and O is oscillation, respectively. '—' means there were no data when the earthquake occurred.

(*6) Qs: Quaternary sediments or sedimentary rocks, Ts: Tertiary sedimentary rocks, Tv: Tertiary volcanic rocks, PTs: Pre-Tertiary sedimentary rocks, PTv: Pre-Tertiary volcanic rocks.

from hydrostatic pressure to lithostatic one, exists under the Niigata sedimentary basin at a depth of 1.5 km or deeper (Xu *et al.*, 1998). Xu *et al.* (1998) and Oki *et al.* (1999) pointed that the effect of the high-pressure thermal water was recognized in shallow groundwater in Niigata prefecture based on their survey of the temperature and water-quality of groundwater and suggested that the high-pressure thermal water rises up along active faults in Niigata Prefecture and makes a significant contribution to local seismic activity.

The 2004 Niigata-Chuetsu earthquake occurred at 17:56 on October 23 (JST). The 2007 Chuetsu-oki earthquake occurred about 40 km northwest of the epicenter of the 2004 Niigata-Chuetsu earthquake at 10:13 on July 16 (JST).

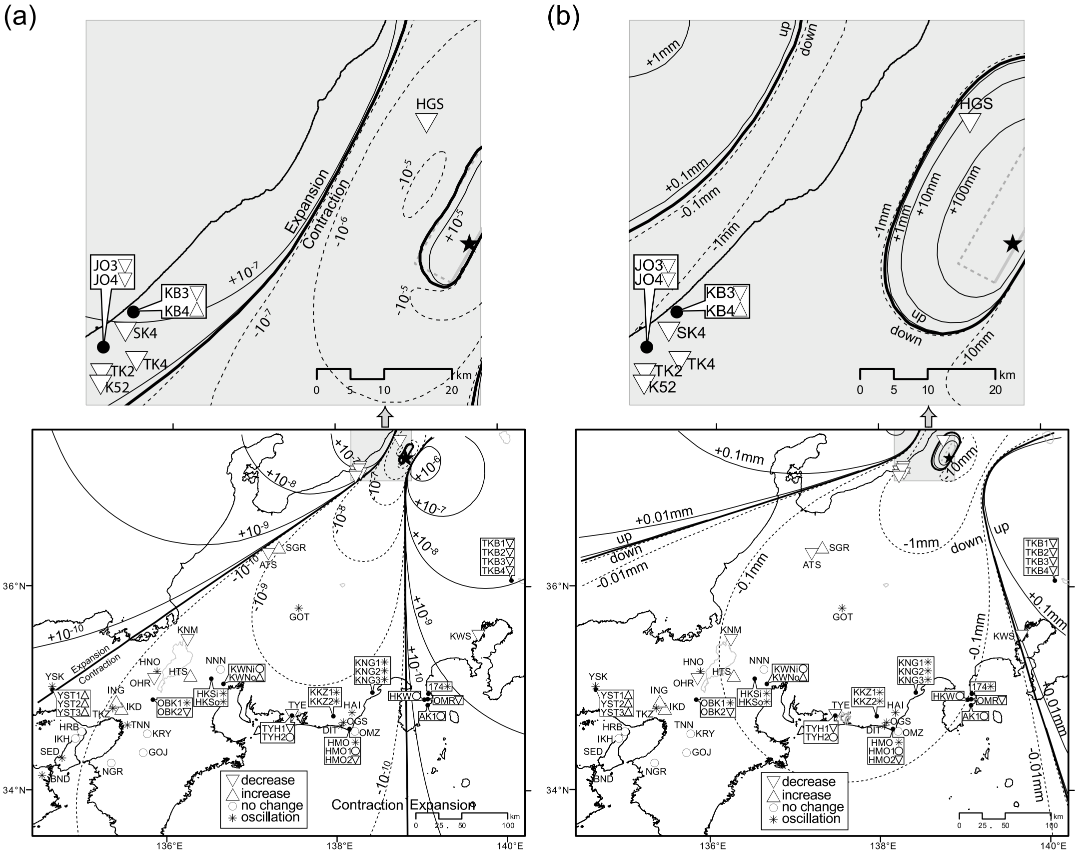

Fig. 1. Coseismic groundwater level changes in response to the 2004 Niigata-Chuetsu earthquake. Contours denote the coseismic volumetric strain changes (a) and vertical surface displacements (b) calculated from the dislocation model of the Geographical Survey Institute (2005).

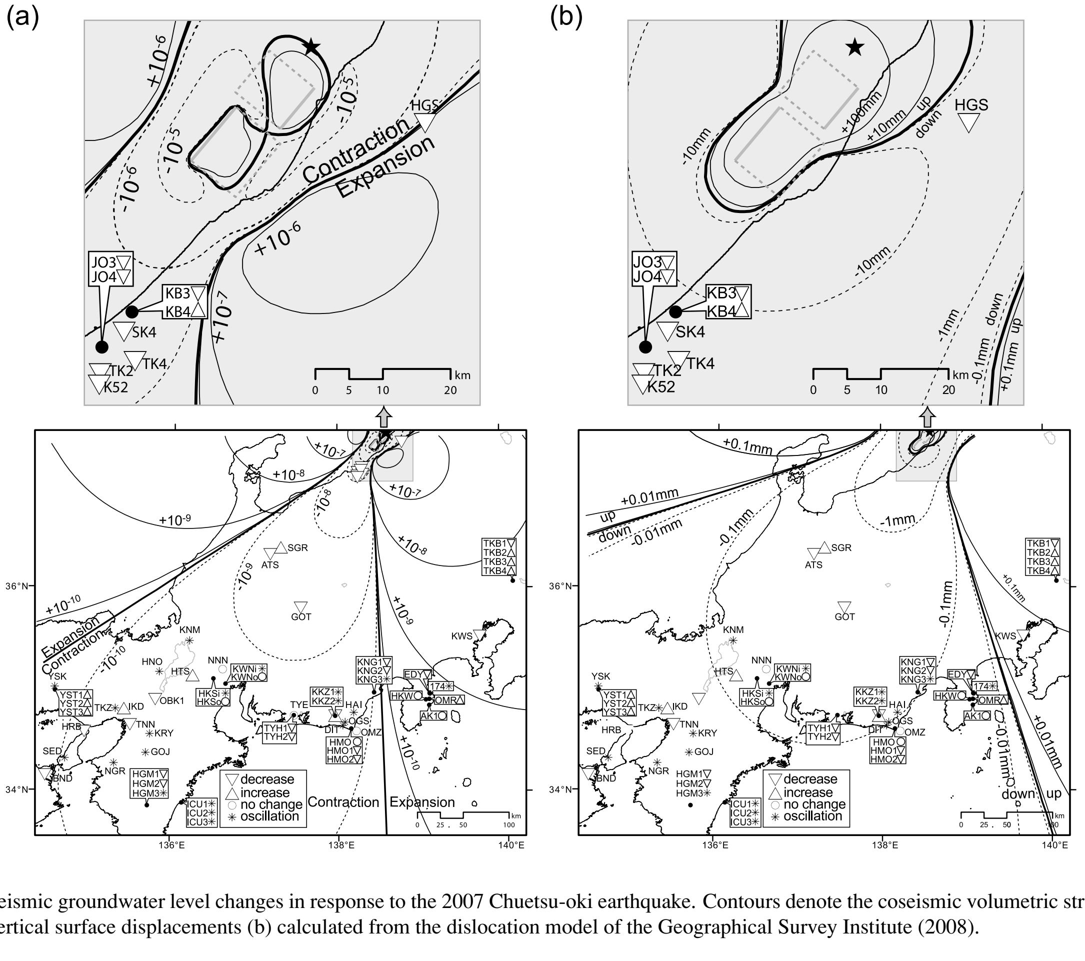

Fig. 2. Coseismic groundwater level changes in response to the 2007 Chuetsu-oki earthquake. Contours denote the coseismic volumetric strain changes (a) and vertical surface displacements (b) calculated from the dislocation model of the Geographical Survey Institute (2008).

The M_{JMA} of the two earthquakes is 6.8. In and around the source region of the 2004 Niigata-Chuetsu earthquake, there are an electrical conductive zone (Uyeshima *et al.*, 2005), a low seismic velocity zone (Okada *et al.*, 2005), and several *S*-wave reflectors (Matsumoto *et al.*, 2005), which also suggest the existence of water in and around the focal region.

Natural gas in Niigata Prefecture is dissolved in the groundwater. Niigata Prefecture also needs groundwater to melt snow on roads in winter. Therefore, a lot of groundwater has been pumped up for a long time, and land subsidence has occurred in Niigata Prefecture (Niigata Prefecture, 2008). In order to monitor the land subsidence, the Niigata Prefectural Office has been observing the groundwater level since the 1960's. In Joetsu city and Nagaoka city, there are nine observation wells of Niigata Prefectural Office (Table 1, Figs. 1 and 2). The sampling interval is 1 h. Geology in and around these observation wells is mainly composed of Quaternary sediments. The nine wells are considered to be situated in the neighborhood of the focal region of the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes.

The Geological Survey of Japan (GSJ), AIST has also been monitoring groundwater since 1970's—for earthquake prediction research. The groundwater observation network of GSJ is now composed of 43 stations (60 wells) in and around the Tokai and Kinki districts (Table 1, Figs. 1 and 2). Some of the groundwater observation stations have two or more observation wells. Therefore, the number of wells is larger than that of the stations. At each station except AK1, the groundwater level in open well or the pressure in the sealed well is observed as pore water pressure in the aquifer. At AK1, the flow rate is observed. For convenience, the data of the groundwater pressure are expressed as those of the groundwater level in this paper. The sampling interval is 2 min for most of the wells and 10 min or 1 s for some of the wells. Most of GSJ wells seem to be far enough from the focal regions for the two earthquakes (Figs. 1 and 2).

To discuss changes in groundwater level or pressure caused by the coseismic static volumetric strain changes, we need the sensitivity of the groundwater level or pressure to volumetric strain changes and the values of the coseismic static volumetric strain changes. As to the groundwater level or pressure changes caused by the coseismic static displacements, we assume that the amplitudes are smaller than the coseismic vertical displacements of the surface. Therefore, we need the fault models of the two earthquakes to calculate the strain changes and vertical displacements at each of the observation wells.

For the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes, various fault models have been reported. Since observed groundwater is shallower than 1 km, we should compare the groundwater level or pressure changes with the static crustal deformation near the ground surface. Therefore, the fault model based on coseismic displacement of the surface is considered to be suitable and we adopted the dislocation models of the Geographical Survey Institute (2005, 2008) in this paper. Using the models, we calculated the coseismic static volumetric strain changes and vertical displacements at each well using a program of Okada (1992) and MICAP-G (Naito and Yoshikawa, 1999). At the nine wells in Niigata Prefecture, the calculated static volumetric strain changes for the two earthquakes larger than 10^{-8} and the static vertical displacements are a few millimeters or larger. On the other hand, the volumetric strain changes are smaller than 10^{-9} and the vertical displacements are the order of 0.1 mm or smaller at most of GSJ wells (Figs. 1 and 2, Table 1).

The groundwater level or pressure sensitivity to crustal volumetric strain changes is presumed by the tidal response of the groundwater level or pressure. Major tidal components (M2 and O1) were extracted from the groundwater level (or pressure) data before the 2007 Chuetsu-oki earthquake using the BAYTAP-G program (Tamura *et al.*, 1991). The amplitude of the tidal volumetric strain at each observation well, which includes the components of the earth and oceanic tides, was calculated using the GOTIC2 program (Matsumoto *et al.*, 2001). From these estimated tidal components, the groundwater level (or pressure) sensitivity at each observation well was determined. The expected water level change caused by the coseismic volumetric strain change can be calculated when this sensitivity is multiplied by the coseismic volumetric strain change calculated above. Since the resolution of the groundwater level (or pressure) data ranges from 0.1 to 1 mm, the strain sensitivity is regarded as 0 in the case that the amplitude of the groundwater level for O1 or M2 is smaller than 0.1 mm. The results are shown in Table 1.

Some observed groundwater in Niigata Prefecture should be confined (Sekiya and Miyajima, 2005). However, the barometric response of the groundwater level is ambiguous, and the strain sensitivity is zero at all of the wells in Niigata Prefecture (Table 1). Therefore, we should neglect the effect of the static volumetric strain changes on the groundwater level in Niigata Prefecture.

3. Results

In the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes, the distributions of the volumetric strain changes and vertical surface displacements were similar in and around the Kinki and Tokai districts, but different in Niigata Prefecture (Figs. 1 and 2). All of the wells except HGS in Niigata Prefecture were in the expansion area in the case of the 2004 Niigata-Chuetsu earthquake but in the contraction area in the case of the 2007 Chuetsu-oki earthquake (Figs. 1 and 2, Table 1). As to the vertical displacements, the wells except HGS in Niigata Prefecture were coseismically sunk

Table 2. Earthquake-related groundwater level (pressure) changes classified by geology of the aquifers of the observation wells.

	Area	Geology	Qs	Ts	Tv	PTs	PTv	Sum*2
2004 Mid-Niigata Prefecture	Niigata	Step	9/9*1	0/0	0/0	0/0	0/0	9/9
		Trend	9/9	0/0	0/0	0/0	0/0	9/9
	Other Areas	Step	5/20	1/9	1/4	1/15	0/5	8/53
		Trend	4/20	1/9	0/4	8/15	1/5	14/53
2007 Niigataken-Chuetsuoki	Niigata	Step	9/9	0/0	0/0	0/0	0/0	9/9
		Trend	8/9	0/0	0/0	0/0	0/0	8/9
	Other Areas	Step	5/20	5/12	1/8	2/13	1/3	14/56
		Trend	9/20	5/12	1/8	7/13	1/3	31/56

(*1) 9/9 means the 9 step-like changes in the 9 wells. The other figures have the similar meaning.

(*2) Some of the wells have no data in the occurrence of one of the two earthquakes (Table 1). Therefore number of the wells is not equal to that in Table 1.

for both of the earthquakes while HGS rose for the 2004 Niigata-Chuetsu earthquake. The amplitudes of the vertical displacements were smaller than 10 mm except the case of HGS for the 2004 Niigata-Chuetsu earthquake, where the amplitude was a few centimeters (Fig. 1). These were smaller than 1 mm or 0.1 mm at GSJ wells. Since they were much smaller than the observed earthquake-related groundwater level changes, the effect of the static displacements can be neglected for the two earthquakes. The seismic intensity distributions were similar for both of the earthquakes. At the wells in Niigata Prefecture, the intensity ranges from ‘5 lower’ to ‘6 lower’ in the scale of the Japan Meteorological Agency (JMA). At GSJ wells, it ranges from 0 to 3 (Table 1).

The earthquake-related groundwater changes seem to depend on the geology of the aquifer. Table 2 shows the relation between the earthquake-related groundwater changes and geology of the aquifer for the wells. The observation wells in Niigata area are all situated in quaternary sediments or sedimentary rocks (Qs in Tables 1 and 2), and the responses for the two earthquakes are almost the same. Therefore, we could not find the differences derived from the geology. However, geology of the Pre-Tertiary sedimentary rocks (PTs) for the observation wells of GSJ seem to produce more trend changes than step-like changes although the other geologies did not show any clear tendencies (Table 2).

3.1 Groundwater changes in Niigata Prefecture

The observed original groundwater level changes related to the two earthquakes in Niigata Prefecture are shown in Figs. 3 and 6 and Table 1. For air pressure and rainfall, we used the data at amedas TAKADA of the JMA.

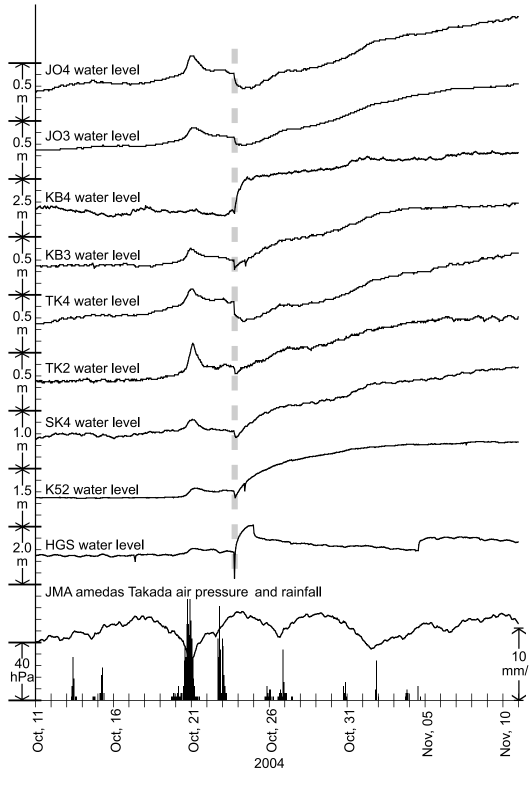

Fig. 3. Observed water level changes at Niigata Prefecture before and after the 2004 Niitata-Chuetsu earthquake. The sampling interval is 1 h.

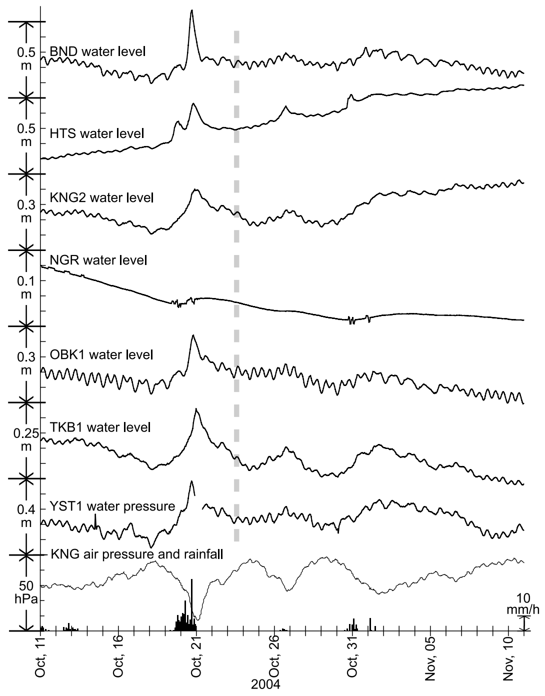

Fig. 4. Examples of observed water level (or pressure) changes at GSJ wells before and after the 2004 Niitata-Chuetsu earthquake. The sampling interval is 1 h.

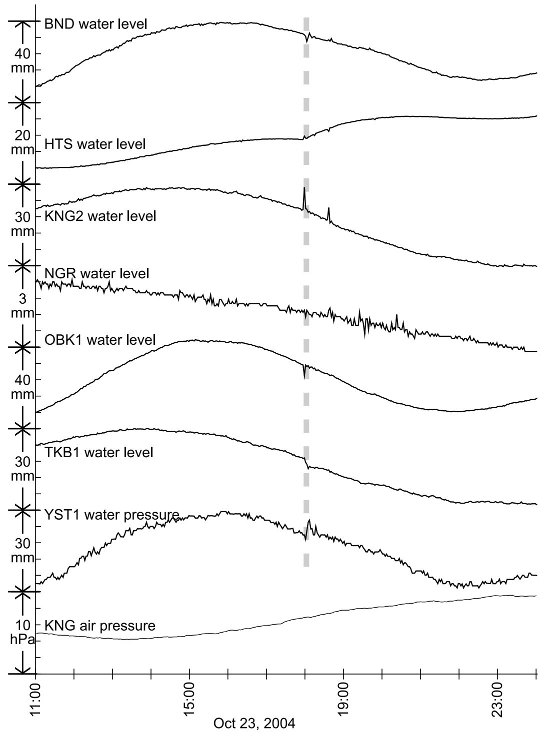

Fig. 5. Examples of observed water level (or pressure) changes at GSJ wells before and after the 2004 Niitata-Chuetsu earthquake. The sampling interval is 2 min.

Before the two earthquakes, there were some changes at most of the wells. However, those changes are also recognized in the areas far from the focal region (Figs. 4 and 7) and their amplitudes do not depend on the epicentral dis-

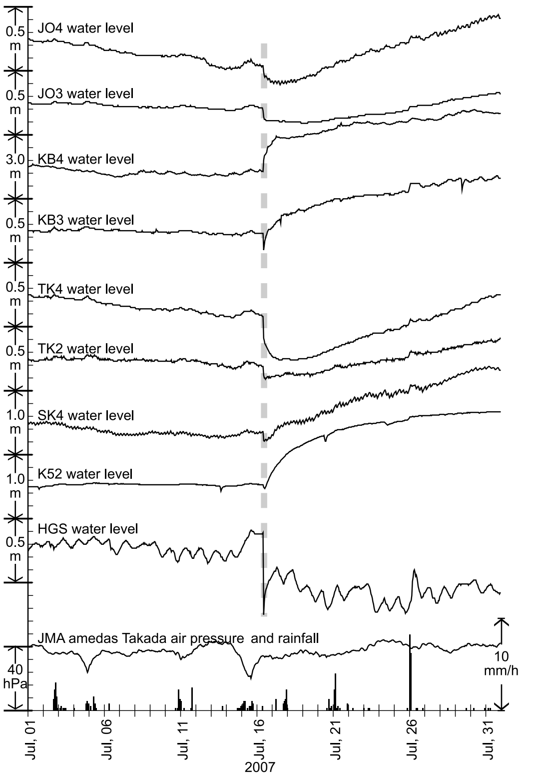

Fig. 6. Observed water level changes at Niigata Prefecture before and after the 2007 Chuetsu-oki earthquake. The sampling interval is 1 h.

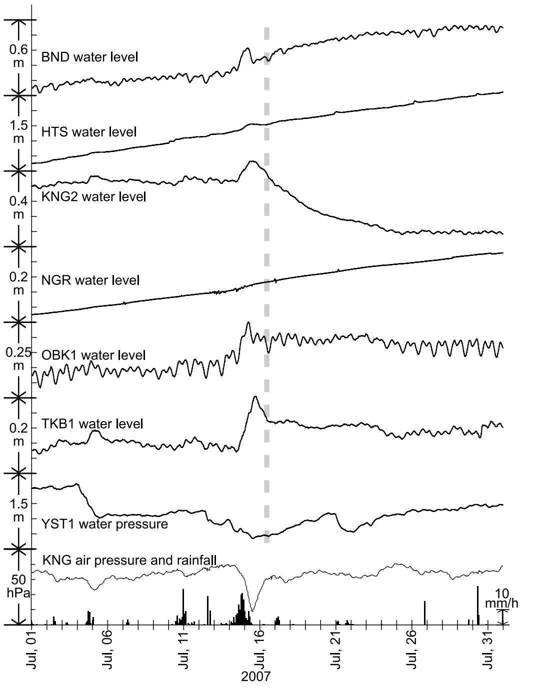

Fig. 7. Examples of observed water level (or pressure) changes at GSJ wells before and after the 2007 Chuetsu-oki earthquake. The sampling interval is 1 h.

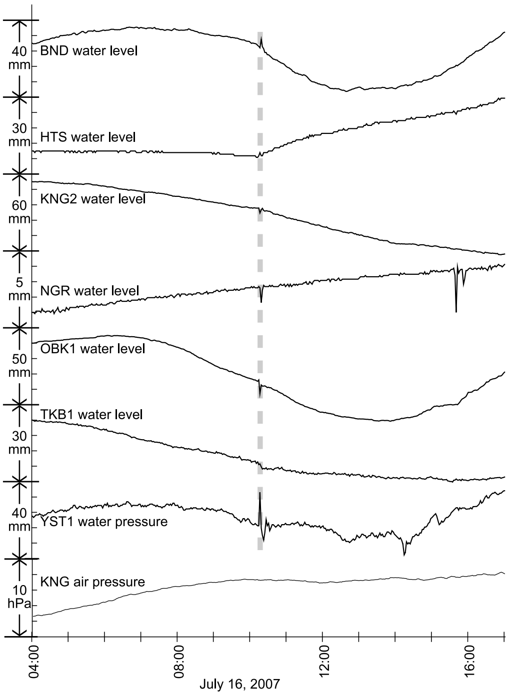

Fig. 8. Examples of observed water level (or pressure) changes at GSJ wells before and after the 2007 Chuetsu-oki earthquake. The sampling interval is 2 min.

tances. Therefore, it is hard to consider that those changes are derived from the focal regions of the two earthquakes. We considered them to be caused by the rainfalls and air pressure changes just before the two earthquakes.

At all of the wells, there were quick rises or drops immediately after the two earthquakes, which will be called 'step-like changes' in this paper. There were also postseismic gradual increases or decreases, which will be called trend changes in this paper. The trend changes continued for several days or longer. The coseismic and postseismic groundwater level changes, which ranged from 0.5 to 3 m, were caused by the ground shaking as mentioned above. The changes at all wells except HGS are very similar for the two earthquakes. The reason for the response at HGS is unknown at present.

3.2 Groundwater changes at GSJ wells

The typical examples of the observed groundwater level (or pressure) changes related to the two earthquakes at GSJ wells, which are far from the focal region, are shown in Figs. 4, 5, 7, and 8 and Table 1. At many of the wells, we detected the small step-like changes and/or trend changes. The groundwater level (or pressure) changes expected from the coseismic volumetric strain changes are smaller than 1 mm at most of the wells and several millimeters at the other wells (Table 1). On the other hand, observed coseismic and/or postseismic changes are much larger than the expected changes. Therefore, it is considered that the coseismic and/or postseismic groundwater level (or pressure) changes were caused by the ground shaking. However, the changes are much smaller than those at the wells in Niigata Prefecture. The coseismic and/or postseismic changes are also similar for the two earthquakes although these are not so remarkable as in Niigata Prefecture (Table 1).

3.3 Recovery of earthquake-related groundwater changes

The long-term water level changes during the period from October, 2004 to March, 2007 at the wells in Niigata Prefecture are shown in Fig. 9(a). As mentioned above,

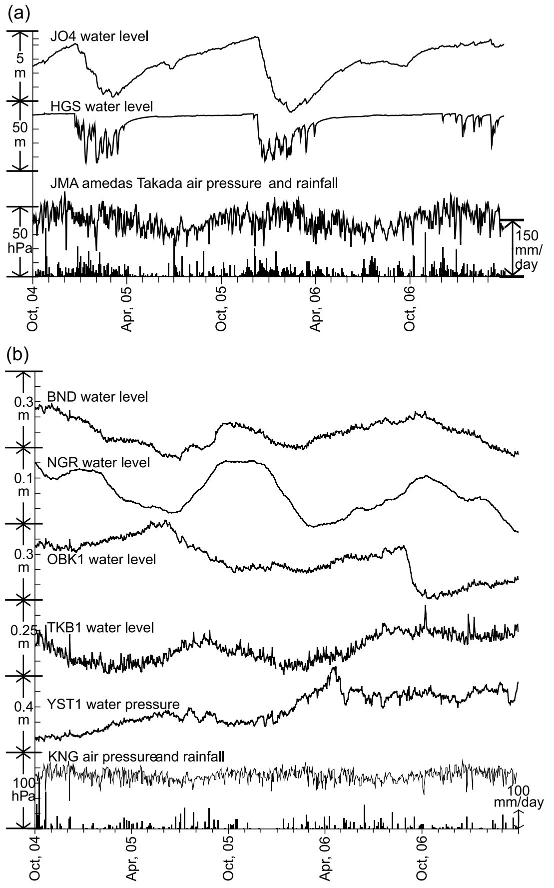

Fig. 9. Examples of the long-term water level changes at the wells in Niigata Prefecture (a) and GSJ wells (b). The sampling interval is 1 day.

since much groundwater is pumped up to melt snow in winter, in general, the groundwater level falls greatly in winter and recovers in the other seasons. As a result, there are clear annual changes, the amplitudes of which range from 4 to 30 m. Groundwater level changes related to the two earthquakes were much smaller than these annual changes. It is difficult to detect coseismic and/or postseismic changes related to the 2004 Niigata-Chuetsu earthquake on October 23, 2004 in Fig. 9(a). Therefore it seems that the groundwater level changes related to the 2004 Niigata-Chuetsu earthquake recovered in Niigata Prefecture before March, 2007.

At the observation wells of GSJ in and around the Tokai and Kinki districts, coseismic and/or postseismic changes were small for the two earthquakes. It is also difficult to detect the earthquake-related changes in the long-term groundwater level changes in Fig. 9(b). They seem to have recovered promptly (Figs. 4 and 7).

Since ground shaking can change physical properties, such as permeability, specific storage, and skempton coefficient, which govern groundwater movement, it is considered that it may take long time to recover earthquake-related groundwater changes caused by the ground shaking. On the other hand, the coseismic static volumetric strain change, which is usually too small to break the aquifer system, cannot change the physical properties and it may take only a short time to recover the earthquake-related groundwater changes. The 11-m drop of groundwater level at a well in the Dogo hot spring, which is considered to be caused by the static volumetric strain change due to the 1946 Nankai earthquake, recovered in about 3 months (Kawabe, 1991) although the 10 m rise of the groundwater level at the same well, which is considered to be caused mainly by the ground shaking of the 2001 Geiyo earthquake, has not been recovered (Itaba and Koizumi, 2007).

In the case of the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes, most of the groundwater level or pressure changes are considered to be caused by ground shaking and we could not find the differences of the recovery times which may depend on the mechanism of earthquake-related groundwater changes.

4. Discussion

As mentioned above, it is considered that the groundwater level or pressure changes of our observation wells associated with the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes were caused by ground shaking. The ground shaking causes consolidation, fracturing, and fracture clearing (e.g., Montgomery and Manga, 2003; Brodsky *et al.*, 2003). According to Montgomery and Manga (2003), consolidation is caused also by crustal stress change. Generally, when liquefaction arises, pore pressure will rise. When consolidation, fracturing, and/or fracture clearing occur, permeability and specific storage (quantity of the water stored per unit volume), which govern groundwater movement, will be changed. When permeability and storage coefficient are changed, pore pressure distribution in the aquifer will be changed.

In Niigata Prefecture, the groundwater level drops at all of the wells except KB4 immediately after the two earthquakes (Figs. 3 and 6). This means that pore pressure fell at those wells immediately after the two earthquakes. When fracturing and/or fracture clearing arise, the specific storage can increase momentarily and the pore pressure may fall locally. On the other hand, liquefaction may have occurred at KB4. With respect to the postseismic gradual increases at all wells except HGS, it is considered that they were caused by diffusion, resulting in the new pore pressure distribution in the whole aquifer. It depends on changes in permeability and specific storage in the whole aquifer system. However, as the effect of such changes are much smaller than that of pumping up in winter, it seems that the earthquake-related changes recovered soon.

The coseismic static volumetric strain changes were smaller than 10^{-9} at most of the observation wells of GSJ. However, there were many coseismic and/or postseismic groundwater level or pressure changes. It seems that these were also caused by the ground shaking and were almost similar for the two earthquakes. At HGM1 and HGM2, which are two wells of the same station in Tertiary sedimentary rocks (Table 1) and sealed, we have been observing groundwater pressure with a sampling interval of 1 s since June 2007. At HGM1 and HGM2, seismometers are also installed on the bottom of the wells. Therefore, we compared the dynamic groundwater pressure changes with the waveform of the seismograph in the case of the 2007 Chuetsu-oki earthquake (Fig. 10). Figure 10 shows that the step-like change in the groundwater pressure started when

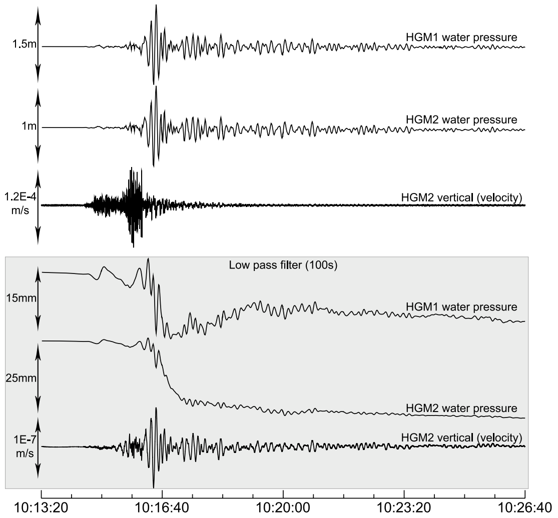

Fig. 10. Observation waveform of the seismograph and water pressure at HGM. The sampling of seismograph and water pressure are 200 and 1 Hz, respectively.

the surface wave arrived. Brodsky *et al.* (2003) showed the same result at a well in granite in Oregon USA, and she explained this result as being caused by fracture cleaning made by the rapid groundwater flow induced by the surface wave. Our result shows that fracture cleaning can occur not only in granite but also in Tertiary sedimentary rocks. If we accumulate such observation results, we will understand the mechanisms of earthquake-related groundwater changes more easily. We plan to increase those high-sampling groundwater observation wells.

5. Conclusions

We have investigated the groundwater changes in Niigata Prefecture and in and around the Kinki and Tokai districts related to the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes. We regarded Niigata Prefecture as the neighborhood of the focal region and the area in and around the Kinki and Tokai districts as the area far from it. The static crustal deformations for the two earthquakes were different in Niigata Prefecture, but similar in and around the Kinki and Tokai districts. The distributions of the seismic intensities were similar for both of the earthquakes. There was no remarkable precursory change in the groundwater level or pressure. There were many coseismic and/or postseismic groundwater level or pressure changes and these were almost similar for the two earthquakes. In Niigata Prefecture, the amplitude of coseismic and postseismic water level changes, which were caused by the ground shaking, ranged from 0.5 to 3 m, but these changes were much smaller than the annual changes. In and around the Kinki and Tokai districts, observed coseismic and postseismic changes, which were also caused by the ground shaking, were small and it seems that they recovered soon. At a certain station in the Kinki district, the step-like change in the groundwater pressure started at the arrival time of the surface wave of the 2007 Chuetsu-oki earthquake.

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