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Changes in groundwater levels or pressures associated with the 2004 earthquake off the west coast of northern Sumatra (M9.0)

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Associated with the 2004 earthquake off the west coast of northern Sumatra, changes in groundwater levels or pressures were observed at many observation stations in Japan which are more than 5000 km from the hypocenter. At 38 of the 45 observation stations, there were changes in groundwater levels or pressures. At the 10 observation stations in which the Ishii-type borehole strain instruments were established, changes in crustal strains were also observed. A major part of the changes in crustal strains and groundwater levels or pressures were dynamic oscillations due to a seismic wave. At some stations, coseismic or postseismic rises or drops were also observed. At five stations where both crustal stain and groundwater levels or pressures were observed, postseismic changes in groundwater levels or pressures were consistent with coseismic static steps in crustal strains. At the other five stations, postseismic changes in groundwater levels or pressures did not agree with the coseismic static steps. At two stations of these five stations, it is anticipated that the pore water pressure change in each aquifer locally occurred independently of the change in crustal strain. At another station, postseismic changes in groundwater level possessed the same characteristics as a model removing the temporary deposition. At the last two stations, the causes of the changes are unknown.

Key words: Sumatra earthquake, groundwater level or pressure, crustal strain, oscillation due to a seismic wave, postseismic changes.

1. Introduction

It is known that groundwater level changes with a seismic wave of a distant earthquake (Rexin *et al.*, 1962). It is thought that dynamic oscillation in crustal strain in an aquifer due to a seismic wave mainly causes dynamic oscillation in the groundwater level.

Cooper *et al.* (1965) and Kunugi *et al.* (2000) showed that the amplitude of the oscillation in groundwater level is enhanced in a particular period due to the characteristics of the well-aquifer system. Woodcock and Roeloffs (1996) compared groundwater level changes with broadband seismograms. On the other hand, Brodsky *et al.* (2003) investigated coseismic groundwater level steps and proposed a new model based on the removal of the temporary deposition barrier due to groundwater flow by seismic wave that causes a coseismic step. These papers mainly discussed groundwater level changes at one well related to seismic waves of several distant earthquakes.

Associated with the earthquake off the west coast of northern Sumatra (Mw 9.0) occurred at December 26, 2004, changes in groundwater levels or pressures were observed at many observation stations of Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Research Center for Earthquake Prediction, Disaster Prevention Research Institute, Kyoto University, Tottori University, Hot Springs Research Institute of Kanagawa prefecture, Yamaguchi University, and Chugoku Electric Power Co. Inc. in Japan. These observation stations are more than 5000 km from the hypocenter. Consequently, it enables us to investigate the characteristics of groundwater level changes at many observation stations to a distant large earthquake. In addition, the Ishii-type borehole strain instruments were installed at some stations of AIST, and we compared the groundwater level changes with the crustal strain changes.

In this paper, we will report the characteristics of the groundwater level changes and crustal strain changes caused by the Sumatra earthquake. Based on the observed dynamic oscillations in crustal strains and groundwater levels or pressures due to the seismic wave, the strain sensitivities of the groundwater levels were estimated for several periods. We will also discuss the postseismic changes in groundwater levels or pressures compared with the coseismic strain steps.

2. Observation

AIST contracted the observation well network mainly in and around Tokai and Kinki districts for earthquake prediction (Fig. 1, Tsukuda, 2000; Tsukuda *et al.*, 2000). To the avoid effects of rainfall and artificial pumping, depths of the wells are from 120 m to 1000 m and the screened depths of the wells are from 80 m to 800 m. There is one well at each station which has single screen as shown in Table 1. However, there are two or more wells at some stations. As a result, there are 45 stations and 62 wells.

Groundwater levels in the open wells or pressures in the

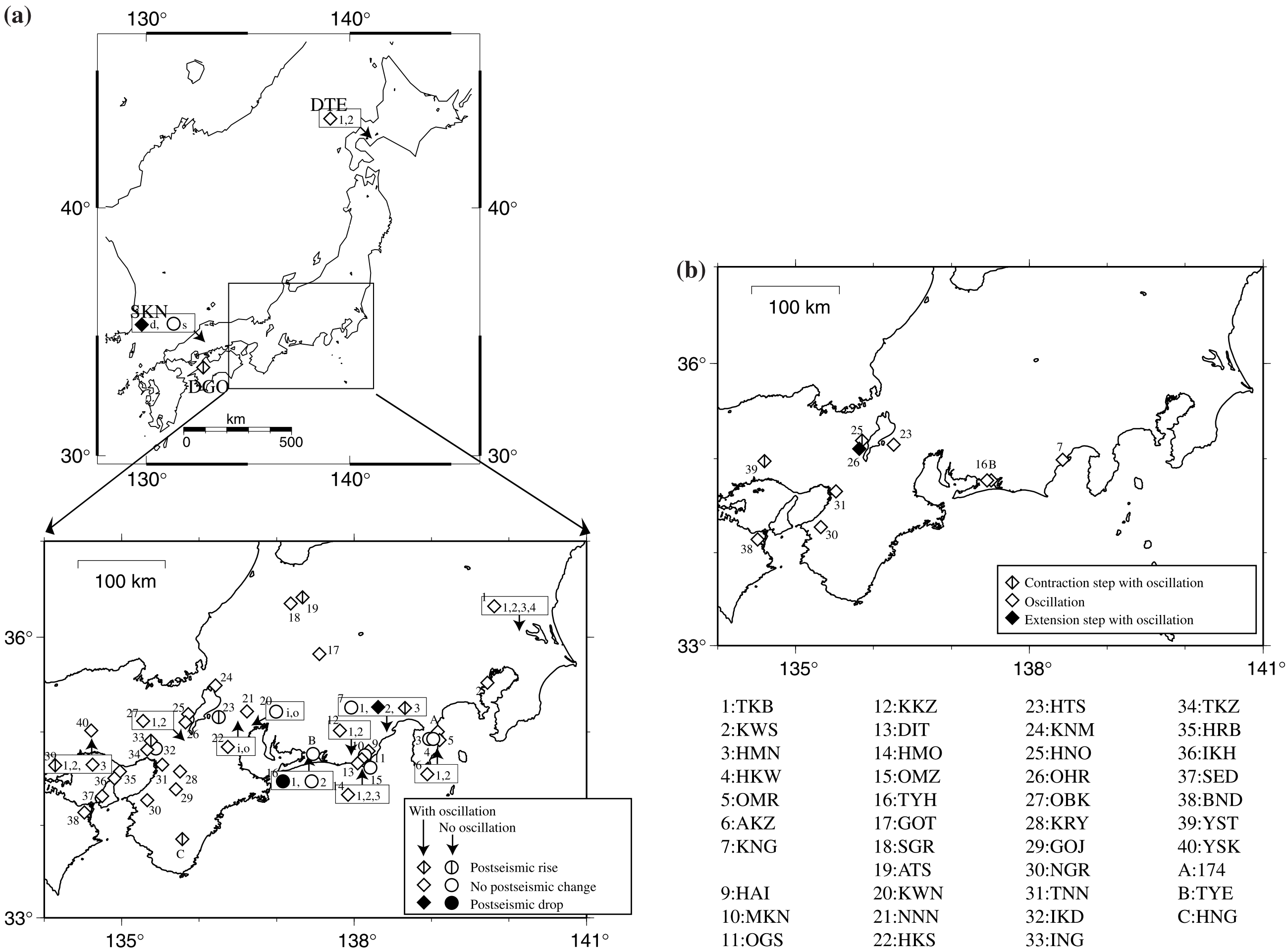

Fig. 1. Locations of observation stations. (a) Changes in groundwater levels or pressures. (b) Changes in crustal strains.

sealed wells are observed. Rainfall and barometric pressure are also observed. At some observation wells, crustal strain fields by the Ishii-type borehole strain instruments are observed (Table 1). The sampling interval of groundwater levels or pressures and crustal strain is mainly 2 minutes. Other sampling intervals are 1 second at HNO and YSK, 5 seconds at SKN, 0.05 seconds at YST, and 10 minutes at HNG and DGO. In addition, the sampling interval of crustal strain at HNO and OHR is 0.05 seconds.

3. Results

The changes in groundwater levels or pressures with the Sumatra earthquake were observed at 38 of the 45 observation stations and 52 of the 62 observation wells. A major part of the changes in groundwater levels or pressures were dynamic oscillations due to the seismic wave. At YSK, the maximum amplitude of the oscillation in groundwater pressure was 0.05 MPa, equivalent to the groundwater level of 5 meters (Fig. 2). Short-period oscillation of groundwater pressure was more clearly detected than that of groundwater level. In the case of an open well, the change in groundwater level needs a groundwater flow between an aquifer and well. Therefore, it is difficult for the groundwater level in an open well to reflect the short-period oscillation in the pore pressure of an aquifer. The effect is called the wellbore storage effect. Therefore, the wellbore storage effect affects changes in the groundwater level as a kind of high-cut filter (Hsieh *et al.*, 1987; Hosoya and Tokunaga, 2003). As oscillation period is shorter, groundwater level change will become smaller. On the contrary, postseismic long-term changes in the groundwater levels or pressures were observed at 11 wells (Fig. 3). There were postseismic rises at eight wells and postseismic drops at three wells. The spatial distribution of postseismic changes did not have a clear tendency. Since borehole strain instruments were also installed at some stations, we will evaluate postseismic changes in groundwater levels or pressures against strain changes in a later section.

At the 10 stations where the Ishii-type borehole strain instruments were installed, dynamic oscillations in crustal strains were observed. The maximum amplitude of the oscillations in the crustal areal strains was on the order of 10^{-6} (Fig. 2). Coseismic static steps in crustal strains were observed at three of the ten stations (Fig. 4). Steps at two stations showed contractions, and a step at one station showed extension. At HNO, a large contractive step in areal strain (-2.4×10^{-7}) was observed.

It is usually thought that pore water pressure responds to crustal volumetric strain, not but to crustal areal strain. Since we observe three components of the horizontal crustal strain, crustal volumetric strain could not be estimated from the observation. However, it is expected that the crustal

Table 1. List of 10 stations where the Ishii-type borehole strain instruments were installed.

Station							Strain	
						Screen	meter	Geology
Name	Well	Code	Latitude	Longtitude	Altitude	depth	depth	
	Number					m	m	
BND		BND	34.141N	134.517E	25	419–430	498	Qs
HNO		HNO	35.186N	135.857E	476	235–246	272	PTs
HTS		HTS	35.151N	136.256E	125	338–360	437	Qs
KNG	WELL1	KNG1	34.988N	138.434E	21	9–20		Qs
	WELL2	KNG2	34.987N	138.433E	21	224–235		Qs
	WELL3	KNG3	34.988N	138.435E	21	309–320	336	Ts
NGR		NGR	34.279N	135.331E	90	402–446	616	Qs
OHR		OHR	35.107N	135.822E	217	256–267	280	PTv
TNN		TNN	34.656N	135.515E	10	447–464	543	Qs
TYE		TYE	34.766N	137.470E	93	186–208	269	PTs
TYH	WELL1	TYH1	34.764N	137.467E	76	182–198	250	
	WELL2	TYH2	34.764N	137.467E	76	135–150		PTs
YST	WELL1	YST1	34.982N	134.611E	126	254–265	288	PTs
	WELL2	YST2	34.982N	134.611E	126	144–150		PTs
	WELL3	YST3	34.982N	134.611E	126	144–150		PTs

Qs: Quaternary sedimentary rocks
Ts: Tertiary sedimentary rocks
PTs: Pre-Tertiary sedimentary rocks
PTv: Pre-Tertiary volcanic rocks

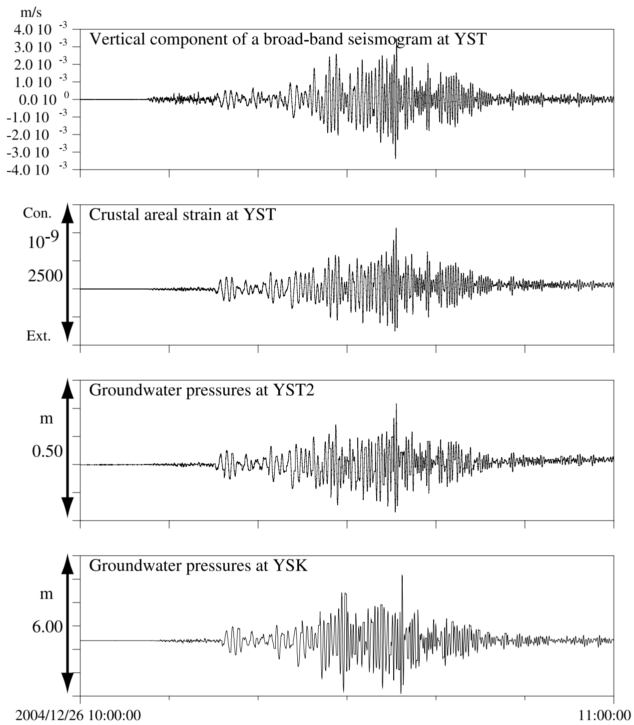

Fig. 2. Observed dynamic oscillations of the vertical component of a broad-band seismogram at YST, crustal areal strain at YST, and groundwater pressures at YST2 and YSK when the seismic wave of the Sumatra earthquake passed through.

areal strain is proportional to crustal volumetric strain at depths of the observation wells where the free surface condition is applicable. The crustal areal strain is 1.5 times as large as crustal volumetric strain assuming the Poisson ratio of the crust is 0.25 (Melchior, 1983). Consequently, we compared changes in the groundwater levels or pressures with changes in the crustal areal strains.

3.1 Characteristics of dynamic oscillations in the groundwater levels or pressures

It is known that the Rayleigh wave phases of the Sumatra earthquake, which traveled around the earth more than five times, are clearly observed using a broad-band seismograph array (Yoshizawa, 2005). We found the groundwater pressure at YSK responded to seismic wave phases that traveled up to four times around the earth (Fig. 5). Comparing the groundwater pressure with the crustal strain at HNO, the oscillation components in the groundwater pressure were very similar to those in crustal areal strain (Fig. 6). Therefore, we believe that the oscillation in the groundwater pressure was caused by a dynamic oscillation in strain of the aquifer due to the seismic wave. Using these oscillation records, the strain sensitivity of the groundwater pressure is calculated in periods between a few tens of seconds and a few hundreds of seconds. As a result, strain sensitivity was estimated to be 0.30–0.35 mm per 10^{-9} areal strain in a period of a few tens of seconds and 0.45–0.50 mm per 10^{-9} areal strain in a period of a few hundreds of seconds. These values are much smaller than the strain sensitivities for M2 (period of 12.4 hours) and O1 (period of 25.8 hours) com-

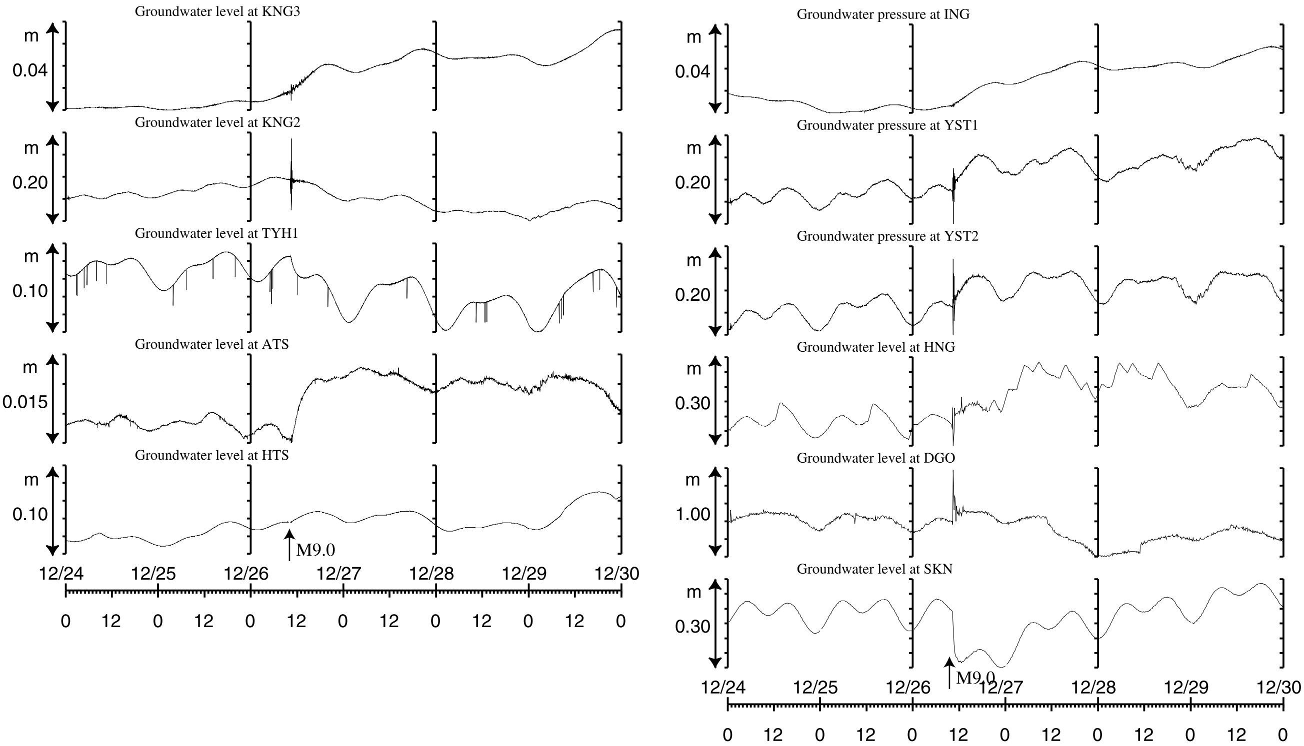

Fig. 3. Some examples of observed postseismic changes in groundwater levels or pressures with the Sumatra earthquake.

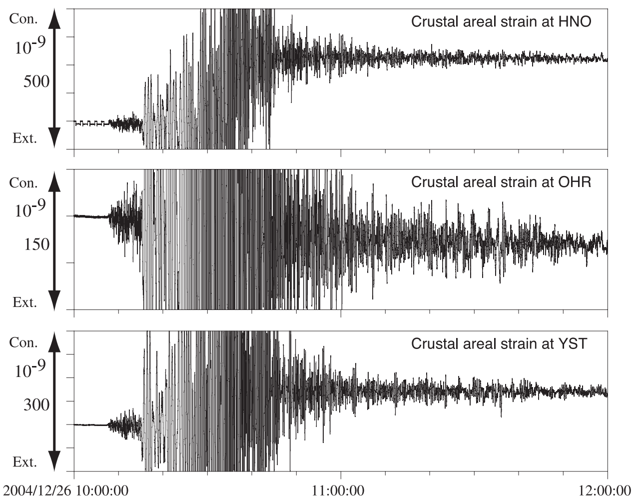

Fig. 4. Observed oscillation and steps in crustal strains due to the Sumatra earthquake.

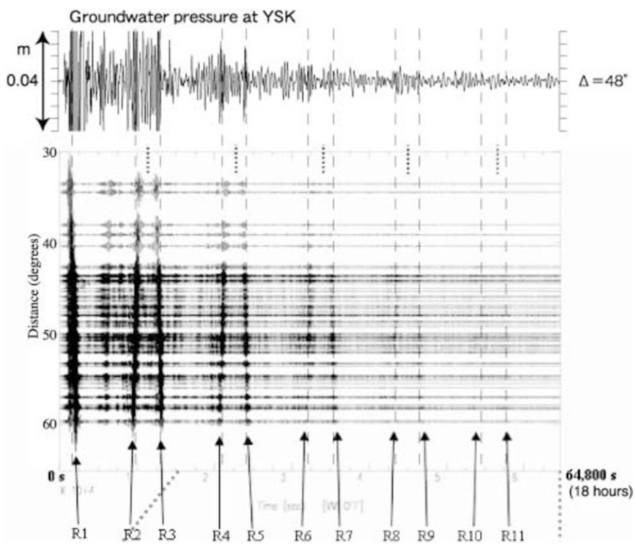

Fig. 5. Dynamic oscillation in groundwater pressure at YSK with the surface wave of the Sumatra earthquake. Upper graph shows groundwater pressure through a band-pass filter with a 200–500 second range. Lower graph was quoted from the Web site of Dr. Yoshizawa (http://noreply.ep.sci.hokudai.ac.jp/~seis/sumatra/). R1 means a Rayleigh wave phase, which directly travels from the hypocenter to the stations through the near side of the earth's surface. R2 means a Rayleigh wave phase, which travels through the far side of the earth's surface. R3, R5, R7, R9 and R11 is a phase, which travels from the hypocenter to stations through the near side of the earth's surface and circle around the earth 1, 2, 3, 4 and 5 times, respectively. R4, R6, R8 and R10 is a phase which travels from the hypocenter to the stations through the far side of the earth and circle around the earth 1, 2, 3 and 4 times, respectively.

ponents of the tidal phenomena (Table 2). The shorter the period is, the smaller the strain sensitivity of groundwater pressure tends to be.

3.2 Characteristics of coseismic strain steps and postseismic changes in groundwater levels or pressures

At 10 stations where the borehole strainmeters are set, we checked for the occurrence of coseismic strain steps and postseismic changes in the groundwater levels or pressures. The postseismic changes in the groundwater levels or pressures were compared with coseismic strain steps using the strain sensitivities of groundwater levels or pressures estimated from the tidal phenomena (Table 2). The results are

Table 2. The strain sensitivities based on tidal responses of groundwater levels using GOTIC2 (Matsumoto *et al.*, 2001) and BAYTAP-G (Ishiguro *et al.*, 1983; Tamura *et al.*, 1991).

Code	Tidal Comp	Phase Shift degree −:Lag	Error	Amplitude mm/10^{-8}	Error	Amp ave
BND	O1	−20.3	5.9	14.53	1.51	12.97
	M2	−15.0	1.0	11.41	0.20	
HNO	O1	−2.6	1.7	15.41	0.44	14.86
	M2	−0.9	0.3	14.31	0.07	
HTS	O1	−55.4	6.5	1.87	0.21	1.38
	M2	−76.0	2.0	0.88	0.03	
KNG1	O1	−285.9	77.3	0.41	0.56	0.35
	M2	−273.6	23.2	0.28	0.11	
KNG2	O1	−0.7	2.2	3.65	0.14	3.98
	M2	6.8	0.4	4.30	0.03	
KNG3	O1	−50.1	20.0	0.73	0.26	0.52
	M2	−69.3	9.6	0.31	0.05	
NGR	O1	−64.6	9.3	0.07	0.01	0.06
	M2	−68.8	6.3	0.05	0.01	
OHR	O1	5.2	2.4	13.64	0.56	13.90
	M2	−0.2	0.3	14.15	0.08	
TNN	O1	−12.2	0.6	5.22	0.06	4.84
	M2	−30.4	0.1	4.45	0.01	
TYE	O1	−71.7	0.9	5.07	0.08	3.92
	M2	−78.2	0.4	2.76	0.02	
TYH1	O1	−47.5	1.4	11.47	0.29	9.32
	M2	−66.1	0.6	7.16	0.07	
TYH2	O1	5.3	1.2	12.96	0.28	13.10
	M2	−12.0	0.4	13.23	0.08	
YST1	O1	−21.4	2.4	8.30	0.03	8.84
	M2	−25.5	0.9	9.37	0.01	
YST2	O1	−9.0	3.2	12.73	0.71	14.22
	M2	−13.9	0.4	15.71	0.12	
YST3	O1	−40.7	2.4	4.87	0.20	4.53
	M2	−34.4	0.4	4.19	0.03	

summarized in Table 3. At YST, the amplitudes and signs of postseismic changes in groundwater pressures agreed with the amplitude and sign of the coseismic strain step. At TYE, TNN, BND and NGR, both the crustal strains and groundwater levels or pressures do not change and seems consistent. Despite there was no coseismic strain step at KNG2, TYH1, and HTS, long-term groundwater level changes occurred after the Sumatra earthquake. Although cosesimic strain steps were observed at HNO and OHR, there were no long-term changes in the groundwater level or pressure. We presumed that these observed strain steps were too large to be explained by large-scale static crustal strain changes due to seismogenic faulting of the Sumatra earthquake.

4. Discussions

When postseismic changes in groundwater levels or pressures did not agree with the coseismic strain steps, the following two mechanisms should be checked. Roeloffs (1998) and Matsumoto and Roeloffs (2003) concluded that repeated postseismic changes in groundwater level were quantitatively explained by the diffusion of abrupt coseismic pore water pressure changes near the well. Brodsky *et al.* (2003) proposed a new model based on the removal of the temporary deposition barrier in a fracture due to groundwater flow by seismic wave that causes a coseismic step-like groundwater level changes due to distant earthquakes. Based on the barrier removal model, coseismic step-like groundwater level changes will not occur again until the recreation of the barrier. The model suggests that coseismic groundwater level change should occur just one time for a series of seismic activity.

At KNG2, TYH1, and HTS, several previous postseismic changes in groundwater levels were mainly the same as the postseismic changes associated with the Sumatra earthquake (Tsukuda, 2000; Koizumi *et al.*, 2002; Takahashi *et al.*, 2002; Sato *et al.*, 2005). In the case of the M7.1 and M7.4 off Kii peninsula earthquakes that occurred within 5 hours on September 5, 2004, postseismic groundwater level

Table 3. List of coseismic steps in crustal strains and postseismic changes in groundwater levels or pressures with the Sumatra earthquake at 10 stations in Table 1. The values of converted volumetric strain are estimated from the postseismic changes in groundwater levels or pressures using the strain sensitivities in Table 2.

	Observed areal strain step		Groundwater level change			Converted areal strain changes from GL change	
Code	Sign +:Ext	Amp 10^{-9}	Sign +:UP	Amp cm	Duration day	Sign +:Ext	Amp 10^{-9}
BND		<5		<2			<23
HNO	−	240		<1			<10
HTS		<30	+	1	<1	−	109
KNG1				0			0
KNG2			−	8	4–5	+	302
KNG3		<10	+	2	2–3	−	577
NGR		<5		0			0
OHR	+	16		<1			<11
TNN		<5		0			0
TYE		<5		0			0
TYH1		<10	−	3	<1	+	48
TYH2				<1			<11
YST1	−	70	+	6	<1	−	102
YST2			+	7	<1	−	74
YST3				<2			<66

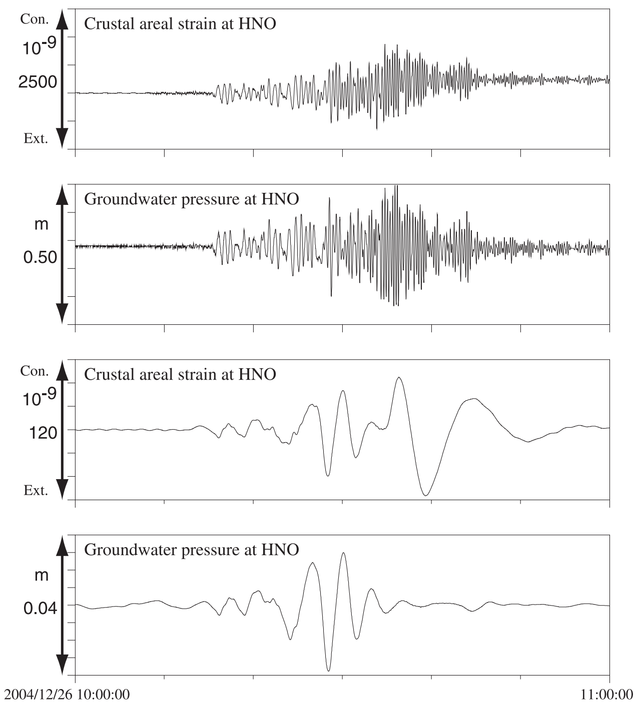

Fig. 6. Dynamic oscillations in crustal strain and groundwater pressure with the Sumatra earthquake. Uppermost and middle-upper graphs show the raw data. Lower-middle and lowermost graphs show the results through a band-pass filter with a 200–500 second range.

drops at KNG2 and TYH1 occurred for both events. On the other hand, at HTS, the groundwater level started to rise after the M7.1 foreshock, but the groundwater level did not change after the M7.4 main shock. At KNG2 and TYH1, postseismic changes in groundwater levels possess the same characteristics as in the cases of Roeloffs (1998) and Matsumoto and Roeloffs (2003). Therefore, it is expected that the mechanism of postseismic changes at KNG2 and TYH1 is similar to that of Roeloffs (1998) and Matsumoto and Roeloffs (2003). At HTS, postseismic changes in groundwater levels possess more similar characteristics as the barrier removal model by Brodsky *et al.* (2003) than the model by Roeloffs (1998) and Matsumoto and Roeloffs (2003).

At HNO and OHR, despite large coseismic static steps in crustal strains, the groundwater levels did not change after the Sumatra earthquake. The possible reason is that groundwater level reflects the average pore pressure change in the aquifer, although the borehole strain sensors mainly detect this change in the vicinity of each well. We have no specific information on the heterogeneity in geology near these stations. However it is hypothesized that crustal strain changes very locally due to the heterogeneity in geological structure in the vicinity of the well while the average pore water pressure in an aquifer cannot change.

5. Conclusions

Changes in groundwater levels or pressures with the Sumatra earthquake were observed at 38 of 45 stations and 52 of 62 wells. Changes in crustal strains were observed at 10 observation stations. It is shown that dynamic oscillations in groundwater levels or pressures respond to dynamic oscillations in crustal areal strains due to a seismic wave. Based on observed oscillations in groundwater pressure and crustal strain at HNO, the strain sensitivity of groundwater pressure is estimated. The shorter the period is, the smaller the strain sensitivity of groundwater pressure is. We compared postseismic changes in groundwater levels or pressures with coseismic strain steps at the 10 stations. Postseismic changes in groundwater levels or pressure and coseismic static steps in crustal strains were consistent at five stations and were not consistent at the other five stations. At two of these five stations, it is presumed that the cause of postseismic changes in groundwater levels is a diffusion of abrupt coseismic pore water pressure changes near a well. At another station, it is presumed that the mechanism of postseismic changes in groundwater level is same as the barrier removal model. However this interpreting is poorly supported by observation results and theories at the present time.

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