Earthquake prediction research based on observation of groundwater

— Earthquake forecasting based on crustal deformation estimated from groundwater level change —

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[Translation from *Synthesiology*, Vol.6, No.1, p.24-33 (2013)]

We constructed a system for detecting preseismic changes in groundwater levels that uses a combination of long-term observation and analysis of groundwater, a poro-elastic theory, and the pre-slip model. This system is now in operation and is contributing to the national project for prediction of the Tokai earthquake. To apply this system to Tonankai and Nankai earthquakes, we constructed an integrated groundwater observation network in and around Shikoku and the Kii Peninsula (Japan). This network is now being used to observe and study groundwater and crustal deformation. Since 2002, we have also been carrying out international cooperative hydrological research for earthquake prediction in Taiwan to help minimize the damage caused by earthquakes in Southeast Asia. We underestimated the magnitude of the 2011 Tohoku earthquake, which was one of the factors that brought about the severe damage in and around the Tohoku area. Therefore, we should examine scientifically the reasons for the underestimation, and advance earthquake prediction research.

Keywords **:** Groundwater, earthquake prediction, crustal deformation, pre-slip, Tokai earthquake

1 Introduction

The earthquake prediction research is a typical *Type 2 Basic Research*. Since the basic researches of earthquakes help in estimating the earthquake occurrences, many results of *Type 1 Basic Research* that are considered useful for earthquake prediction (practical earthquake forecasting) have been reported, but it is extremely difficult to predict earthquakes simply by integrating such researches. The earthquake prediction research by groundwater observation is no exception. In Japan, the earthquake prediction research by groundwater observation started from the “Partial Review of the 3rd Earthquake Prediction Plan,” a proposal of the Geodesy Council, Ministry of Education, Science, and Culture in July 1975. Initially, major participants were the University of Tokyo, Nagoya University, Kyoto University, and one public research institute, Geological Survey of Japan, Agency of Industrial Science and Technology, which is currently Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology. Both are called GSJ, AIST for short. However, it was later found that academic papers of worthy results are not always obtained although observation over a long period of time and a large expenditure is needed. Therefore the researches at the universities stagnated, and only GSJ, AIST continued to engage actively in the observation and research in the late 1990s. This was because continuous research was more acceptable at public research institutes than at universities. Also, in the Tokai Earthquake Prediction Project based on the Act on Special Measures Concerning Countermeasures for Large-Scale Earthquakes (hereinafter, Large-Scale Earthquake Act) established in 1978, GSJ, AIST was in charge of the groundwater observation, and thereinafter, the observation and research of groundwater for earthquake prediction was deemed to be the social responsibility of GSJ, AIST. Hence, GSJ, AIST survived the “period of nightmare”[1] of the *Type 2 Basic Research*.

2 Significant groundwater changes before and after the past Nankai earthquakes

From the Suruga Trough to Nankai Trough located off the coast of Tokai to Shikoku, the giant earthquakes of M8 class occurred repeatedly at intervals of about 100 to 200 years (Figs. 1, 2). Historically, the earthquakes that fractured both the Suruga Trough and the east side of the Nankai Trough, which is the area from the Kumanonada to Enshunada, have been also called the Tokai earthquakes. However, in this paper, the earthquake that occurs in the Suruga Trough is simply called the Tokai earthquake, the earthquake that occurs in the east side of the Nankai Trough is called the Tonankai earthquake, and the earthquake that occurs in the west side of the Nankai Trough is called Nankai earthquake (Figs. 1, 2).

The Nankai earthquakes or the giant earthquakes that occur off the coast of Shikoku and Kii Peninsula are recorded frequently in the ancient documents. It is probably because

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Original manuscript received March 12, 2012, Revisions received June 12, 2012, Accepted July 10, 2012

there were extensive damages due to the Nankai earthquakes in and around Kyoto, the ancient capital. They are one of the groups of giant earthquakes whose history of occurrence is best recorded. Of the past eight Nankai earthquakes, the water level or discharge at Dogo Hot Spring (near N10, Fig. 1) of Matsuyama City, Ehime Prefecture dropped significant four times due to the earthquakes, and that of Yunomine Hot Spring, Hongu-cho, Wakayama Prefecture (near N5, Fig. 1) decreased four to five times (Fig. 2). However, it is not well known whether these had occurred before the earthquake or not. In the 1946 Nankai Earthquake (M8.0), the well water, which was shallow groundwater and probably unconfined groundwater, in 11 places along the Pacific coast from Kii Peninsula to Shikoku ran dry ten days before to immediately before the earthquake,[3] and it is estimated that the water level dropped several tens of centimeters or larger (Fig. 3). “Unconfined groundwater” will be explained later. In Katsuura (Fig. 3), the discharge of the hot spring decreased six hours prior to the earthquake. There were a total of 12 places where the groundwater level or hot spring discharge decreased before the earthquake, and such places were distributed widely along the Pacific coast from the Kii Peninsula to Shikoku (Fig. 3). However, there were over 160 places surveyed by the Hydrographic Bureau, Coast Guard Japan.[3] Therefore the incidence of this preseismic groundwater decrease is very low. Such decrease of groundwater level before an earthquake is also known to have occurred along the Pacific coast of Shikoku and Kii Peninsula before the 1854 Nankai Earthquake.[4]

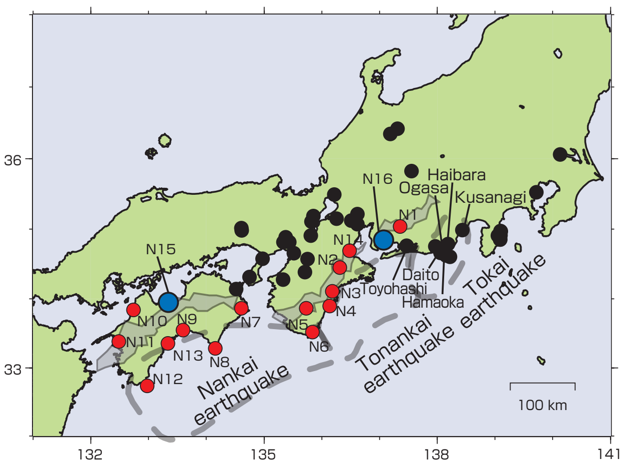

Fig. 1 Assumed focal region (dashed line) of the Tokai, Tonankai, and Nankai earthquakes, and the AIST groundwater observation network for earthquake prediction research

● (black): observation stations constructed before FY 2004. ● (red): new observation stations N1-N14 constructed after FY 2006. ● (blue): observation stations N15-N16 that are currently being constructed. The grey area in the inland area from Shikoku, Kii Peninsula, to Aichi Prefecture shows the region where the short-term slow slip events and deep low-frequency tremors occur regularly. Yunomine Hot Spring is located near the N5 observation station, and Dogo Hot Spring near the N10 observation station. As to Yunomine and Dogo hot springs, see Fig. 2.

3 Correlation between groundwater and earthquake shown by the poro-elastic theory

As mentioned above, it has been known in Japan since ancient times that the groundwater sometimes changes before earthquakes. Wakita (1978)[5] summarized the cases in a table. However, these were merely observed facts, and the theory that correlated the earthquake and groundwater was weak. Therefore the methodical research started in Japan quite late, from 1975.[6] One of the reasons for the activation of research in 1975 was the proposal of the dilatancy-diffusion model.[7][8] This model is explained as follows: the stress accumulation makes cracks increase and groundwater flows into the cracks, which reduces the strength of the region, and then earthquakes occur in the region. The dilatancy-diffusion model offered a theoretical basis for the relationship between groundwater and earthquakes. However, when the dilatancy-diffusion model lost support later,[9] the groundwater observation also lost the theoretical basis. Instead, the theoretical base was offered by the poro-elastic theory.

The elastic theory describes the relationship between the force (stress) and deformation (strain) of an elastic body, and the earthquake and crustal deformation (deformation of the ground) can be theoretically correlated by the elastic theory. The earthquake and crustal deformation can be linked by regarding the earthquake as the discrepancy of fault, which causes the deformation. The relationship between the earthquake and crustal deformation, which is observed by the GPS, strainmeter and so on, can be generally explained by the elasticity theory. Since there are only two variables, stress and strain, in the elasticity theory, there is no room for

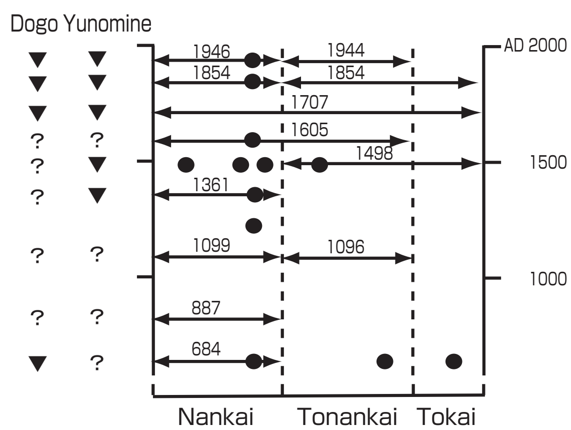

Fig. 2 History of occurrences of the Tokai, Tonankai, and Nankai earthquakes, and decrease in discharge and water level at the Dogo and Yunomine hot springs

▼ indicates decrease. ? shows that there is no record of groundwater changes in the ancient documents. ● is the mark caused by earthquake such as liquefaction. This figure is modified from Sangawa (1992).[2] Considering these results, the N5 observation station was constructed near the Yunomine hot spring, and the N10 observation station near the Dogo hot spring.

the involvement of groundwater.

On the other hand, the poro-elastic theory considers an elastic body with pores, and shows the mutual relationship among stress, strain, water pressure in pores, and amount of water in pores (hereinafter, will be called water content) under the condition that the pores are filled with water.[10]-[12] Considering water in pores = groundwater, and water pressure in pores = pore pressure = groundwater pressure = groundwater level, then the groundwater and crustal deformation can be correlated using this theory. From the standpoint of the poro-elastic theory, groundwater and crustal deformation are closely related, and it is necessary to observe the groundwater to understand crustal deformation accurately. Therefore, by applying this theory, the groundwater and earthquakes can be theoretically linked through the crustal deformation. Actually, it is difficult to grasp the water content and pore pressure in the focal region, which is located deep in the earth. In our current analysis, the elastic theory is applied to the crustal deformation due to the discrepancy of the fault in the focal region, and the poro-elastic theory is applied to the relationship between the crustal deformation and groundwater change.

To represent the relationship between the crustal deformation and groundwater change, the following proportional relationship equation is used for the change in crustal volume change (volumetric strain change ε) and the change in groundwater pressure (p), where it is assumed that crustal deformation in the event of an earthquake is sufficiently faster than the movement of groundwater, and therefore there is no change in water content:

$p = k\varepsilon$ (1)

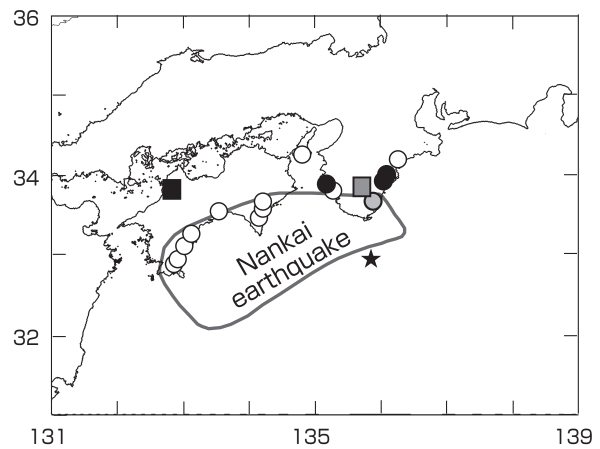

Fig. 3 Decrease in groundwater level and other groundwater changes before the 1946 Nankai Earthquake

○: 11 points where the water level of shallow wells decreased. ●: Three points where the water of shallow wells became clouded. ◯ (grey): Katsuura point where the hot spring discharge decreased. ★: Epicenter of the 1946 Nankai Earthquake. Area surrounded by solid line: Assumed focal region of the Nankai earthquake. ■: Dogo hot spring. ■ (grey): Yunomine hot spring.

The volumetric strain change is calculated from the observed groundwater pressure change, and the reverse can be done. Here, k is the so-called sensitivity of the groundwater pressure against the volumetric strain change (hereinafter, will be called the volumetric strain sensitivity).

The sensitivity k, which is needed to convert the groundwater pressure change to the volumetric strain change, is generally estimated by the change in p due to the tidal volumetric strain change (scale of about 10^{-7} in Japan), which is caused by the surface deformation from the gravity of the moon and the sun (the earth tide). The groundwater is generally divided into unconfined groundwater and confined (artesian) groundwater. The unconfined groundwater, which is located in the aquifer on the impermeable stratum or bedrock, has a free surface where the atmospheric and water pressures are balanced. The confined groundwater is located in the aquifer between the impermeable strata or bedrocks and has no free surface. In unconfined groundwater, which is shallow groundwater in general, k is quite small, and the tidal change in water level is not detected for the volumetric strain change of about 10^{-7}. On the other hand, the change is detectable in the confined groundwater, which is generally deep groundwater and hot spring. k, which varies from place to place, is around 0.1~10 (cm/10^{-7}).[13][14] Figure 4 shows the observation results for March 1~15, 2012 at N14 observation

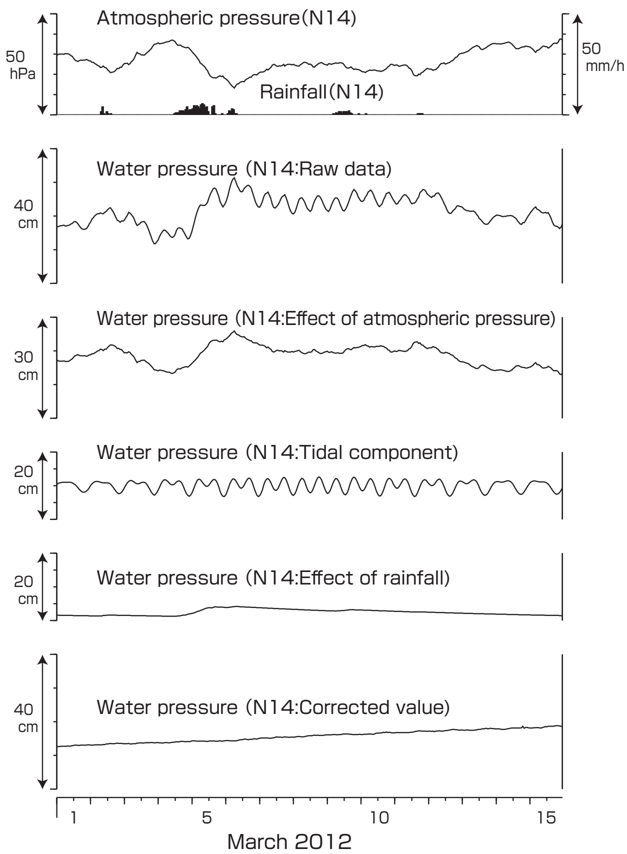

Fig. 4 Example of observation of water pressure change at N14 station (Fig. 1)

The water pressure is converted to the unit of water level.

station (Fig. 1) located in Tsu City, Mie Prefecture. At this observation station, the groundwater level appears above the ground surface, so the water pressure is measured by sealing the well. In the raw water pressure data, semidiurnal and diurnal periodical changes can be seen in addition to the changes due to atmospheric pressure and rainfall and these periodical changes are caused by the tidal changes in volumetric strain. Using the program to remove the effects of the tide, atmospheric pressure and rainfall on groundwater level (water pressure) statistically[15] and separating each component, about 6 cm tidal component is observed at peak to peak amplitudes. It can be seen that there was almost no change during this period when the effects of atmospheric pressure, rainfall and the tide were removed.

4 Forecasting the Tokai, Tonankai, and Nankai earthquakes and groundwater observation by AIST

As shown in Fig. 2, the M8 class giant earthquakes that occurred most recently in the Suruga to Nankai Trough are the 1944 Tonankai Earthquake (M7.9) and the 1946 Nankai Earthquake (M8.0). In these two earthquakes, the focal region did not reach the Suruga Trough. Therefore, a giant earthquake (Tokai earthquake) is thought to occur soon in the Suruga Trough. The government initiated the earthquake prediction project after establishing the Large-Scale Earthquake Act in 1978.

GSJ, AIST carried over the project of the Geological Survey of Japan of the Agency of Industrial Science and Technology, constructed the groundwater observation stations in the Tokai region and has been providing the observation data to the Japan Meteorological Agency (JMA). It has also been one of the expositors of the Earthquake Assessment Committee for Areas under Intensified Measures against Earthquake Disaster. Through these activities, GSJ, AIST has been a member of the governmental earthquake prediction project[16][17] By the long-term observation of the groundwater in the Tokai region, we understood the characteristics of the groundwater changes for each observation station under normal conditions, developed the program statistically to remove the effects of atmospheric pressure and rainfall on groundwater as shown in Fig. 4,[15] and improved the S/N of groundwater observation. In addition, by applying the poro-elastic theory, we estimated the volumetric strain change through groundwater observation. As a result, we are able to evaluate the S/N of groundwater observation quantitatively in comparison with that of volumetric strain observation. In the observed groundwater level (pressure) and discharge, changes such as the long-term increase and decrease generally remain as shown in the corrected value of Fig. 4, even if the effects of atmospheric pressure, rainfall, and the tide are removed. A few mm to a few cm water level changes may also remain even in a short-term period of 24 hour or less. Such changes may be considered “noise.” When there is a change that surpasses such a noise level, it can be detected as an abnormal groundwater change. Such noise also exists in the case where the volumetric strain is directly observed. The noise level of the groundwater observation and that of volumetric strain observation cannot be compared directly. However, by using the aforementioned *k*, the groundwater data can be converted and compared to the volumetric strain data. Figure 5 compares the noise level of AIST groundwater observation to that of JMA volumetric strain observation (as of 1999). Since the estimation of noise from changes over a long term is difficult for both groundwater level and strain, the noise levels within the differences of short time spans such as 1 hour, 3 hours, and 24 hours are estimated. JMA did not remove the rainfall’s effect on the strainmeter in 1999 and calculated the noise levels for the rainy period and the normal period (without rainfall), respectively. In contrast, AIST removed rainfall’s effect on the groundwater level and therefore there is no distinction like JMA. The noise level of AIST groundwater observation is about the same to several times larger than that of JMA’s volumetric strain observation. Considering the fact that the price of the groundwater observation devices such as the water level meter is about one-tenth to one-hundredth of the price of the volumetric strainmeter, the cost performance of groundwater observation is significantly high. As it will be explained later, groundwater level is observed even in countries and regions where the expensive crustal deformation observation devices are not affordable. Therefore this groundwater observation

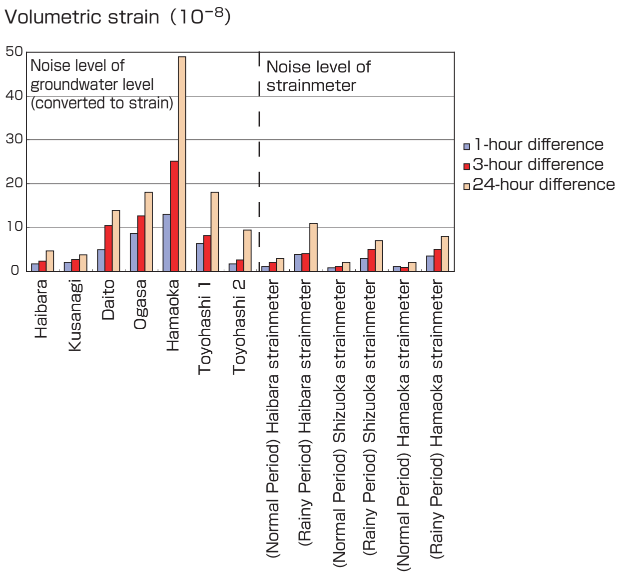

Fig. 5 Comparison of the noise levels at major AIST groundwater observation stations in the Tokai region (seven sets of graphs on left; refer to Fig. 1 for the location of observation stations) to that of JMA volumetric strainmeter[18] (six sets on right) {this figure is modified from Matsumoto and Kitagawa (2005)[19]}. There are two observation wells at Toyohashi, called Toyohashi 1 and Toyohashi 2.

and analysis can be more universally used for earthquake prediction.

As we entered the 21st century, the imminent threat of the next Tonankai and Nankai earthquakes increased,[20] and the Act on Special Measures concerning Advancement of Countermeasures against Disasters of Tonankai and Nankai Earthquakes was enforced in 2003. This law states that the countermeasures must be taken for earthquake disaster prevention in the regions such as the Shikoku and Kii Peninsula, which may be affected by the Tonankai and Nankai earthquakes. The law also encourages public institutes to prepare observation facilities and to do research of earthquakes. In such a situation, to forecast the Tonankai and Nankai earthquakes, AIST started to construct new groundwater observation facilities in and around the Shikoku and Kii Peninsula from FY 2006 and constructed 14 stations by the end of FY 2011, with two more new stations currently under construction (Fig. 1). These will be discussed in subchapter 4.3.

4.1 Detection of the pre-slip of Tokai earthquake by groundwater observation

At present, the most promising preseismic phenomenon of the Tokai earthquake is the slow slip (pre-slip) that occurs in and around the future seismogenetic area right before the earthquake. Figure 6 shows the upthrust/subsidence and expansion/contraction of the ground and the accompanying groundwater level changes when a reverse fault type slip occurs at the plate boundary. If such a slip occurs immediately before the earthquake and the accompanying crustal deformation can be detected beforehand, it may be possible to predict the earthquake.

In 2003, JMA announced the Tokai earthquake prediction scenario by detecting the crustal deformation due to the pre-slip.[21] Since we were able to evaluate the groundwater level change as volumetric strain change, we soon created a quantitative earthquake prediction method using the groundwater observation.[17] By using this method, it was possible to evaluate the groundwater level change quantitatively, in a similar way as using the crustal deformation observation devices such as the strainmeter, tiltmeter, and GPS. Figure 7 shows a simulation of the groundwater level changes at groundwater observation stations of AIST and the volumetric strain changes at observation stations of JMA when an assumed pre-slip of magnitude 6.5 occurs beneath AIST Haibara observation station. As described above, the noise level of AIST groundwater observation is the same to several times larger than that of JMA's volumetric strain observation. Therefore AIST groundwater observation detects the pre-slip at the same time or later than JMA's volumetric strain observation. If such changes actually occur, since the groundwater observation, which is independent from strain observation, can be also explained by the pre-slip, the detection of the pre-slip is considered to be more reliable. Of course, since the water level changes differ according to the place and magnitude of the pre-slip, we made it possible to compare the observed values to calculated ones in every case by conducting similar calculations by changing the magnitudes and places of pre-slips in and around the assumed focal region of the Tokai earthquake.[17] The set of these procedures from observation to analysis is called “the system for detecting preseismic changes in groundwater levels.” This system is considered to increase the accuracy of the detection of precursory phenomena by observing groundwater, and to contribute to improvement in reliability of the overall method for Tokai earthquake prediction.

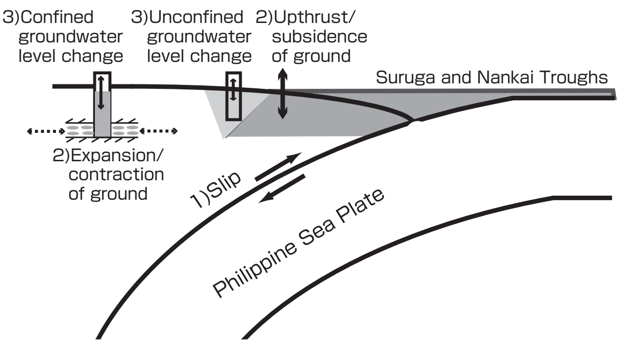

Fig. 6 Schematic figure showing the upthrust/subsidence and expansion/contraction of the ground when reverse fault slip occurs at the plate boundary and the occurrence of groundwater level change accompanying such deformations

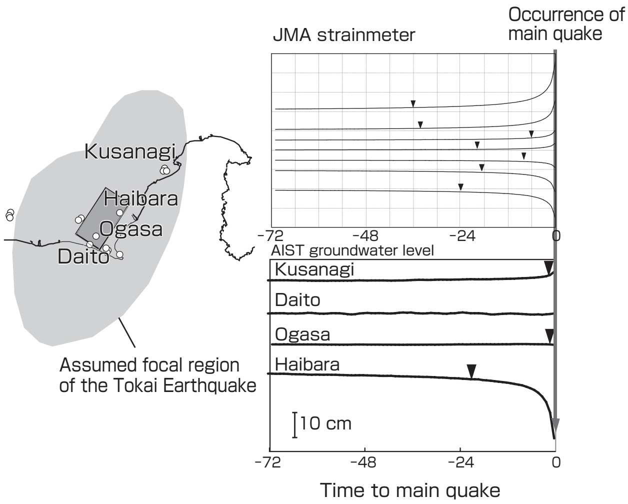

Fig. 7 Simulation of groundwater level change accompanying pre-slip[17][22]

The small open circles on the left show the positions of AIST groundwater observation stations. The grey pear-shaped zone is the projection of the assumed focal region of the Tokai earthquake onto the land area. The graph on the right is the calculation of the changes that may occur in the JMA strain data and AIST groundwater level data when a M6.5 class pre-slip occurs over 72 hours in the fault shown in the grey rectangle within the assumed focal region on the left. When the data exceed the noise level, ▼ is placed to indicate “significant change.”

The groundwater observation data in the Tokai region is sent real time to JMA via AIST, and is under 24-hour monitoring at JMA to predict the Tokai earthquake. This means that the stable groundwater observation in the Tokai region by AIST serves its role as a social outcome.

4.2 Interpretation of the past groundwater change before the Nankai earthquake based on the pre-slip model

We considered the groundwater decrease before the Nankai earthquake described in chapter 2 based on the aforementioned pre-slip model. When there is a reverse fault slow slip (pre-slip) before the Nankai earthquake at the plate boundary in the Nankai Trough, the ground is upheaved and the volumetric strain increases in wide areas from Shikoku to Kii Peninsula before the earthquake. The confined groundwater level may decrease as described above when the volumetric strain increases. Although the unconfined groundwater is insensitive to the volumetric strain, since the unconfined groundwater near the coast is in pressure equilibrium with seawater, the groundwater level will decrease in correspondence to the relatively decreased seawater level (looking from the land surface) when the ground is upheaved (Fig. 6). Therefore, the decrease of groundwater level and hot spring discharge before the past Nankai earthquake can be explained, though qualitatively, by the pre-slip model.

For the preseismic decreases of unconfined groundwater in the 1946 Nankai Earthquake, the decrease of water level over several tens of centimeters cannot be explained because the calculated upthrust is several centimeters at most according to the pre-slip model which was suggested by the Disaster Prevention Research Institute, Kyoto University in 2003.[23] In the model, the slip of about 10 % of the main quake was assumed in a part of the fault of the 1946 Nankai Earthquake. On the other hand, since the volumetric strain increase according to the model is large, the decrease of over several tens of centimeters is possible for the confined groundwater level.[16] However, the fact is that well water, which was shallow unconfined groundwater, decreased in 11 places. The discharge of the hot spring, which was possibly confined, decreased only in one place or Katsuura. Therefore, to explain the groundwater changes before the 1946 Nankai Earthquake using the model in Fig. 6, a special mechanism where the unconfined groundwater changes significantly is necessary in addition to the minute crustal deformation due to the pre-slip. One possible mechanism is as follows: firstly the confined groundwater pressure drops, and the water travels from unconfined to confined aquifer, and therefore the unconfined groundwater level also decreases. As mentioned above, the number of incidences of groundwater level decrease before the 1946 Nankai Earthquake was very low. It might be because the places where such special mechanism existed were limited.

4.3 Design and preparation of the new observation system

To apply the "system for detecting preseismic changes in groundwater levels" designed for the Tokai earthquake to the Tonankai and Nankai earthquakes, and to clarify the mechanism of groundwater level decrease that occurred in the past Nankai earthquakes, AIST made 16 integrated groundwater observation stations, including those that are under construction, from FY 2006 to FY 2012 in and around the Shikoku and Kii Peninsula (Fig. 1). We link these new stations to the observation network in the Tokai region and analyze all the data together.[22] The new observation stations were selected by considering the places where the groundwater changed before/after the past Nankai earthquakes (Fig. 3), the places close to the assumed focal region of the Tonankai and Nankai earthquakes (Fig. 1), and the places where short-term slow slip events and deep low-frequency tremors, which will be explained later, occurred (Fig. 1). Since the Tokai earthquake occurred together with the Tonankai and Nankai earthquakes historically (Fig. 2), these observations and analyses are expected to help predict the Tokai earthquake.

At the AIST new observation stations in and around Shikoku and Kii Peninsula (N1-N14 in Fig. 1), the observations of strain, tilt, and earthquake are conducted in addition to groundwater observation. In the case where there is no nearby GPS observation station of the Geospatial Information Authority of Japan (GSI), GPS is also equipped. In the past Nankai earthquake, not only the deep groundwater or hot spring, which is thought to be confined, but shallow unconfined groundwater also changed preseismically (Fig. 3). As mentioned above, since the groundwater may move vertically, three wells with different depths were drilled to observe the water level (pressure) and temperature (Fig. 8). Similar observations are scheduled for the N15 and N16 observation stations that are currently being constructed. The observation data are sent to AIST and then relayed to JMA in real time.

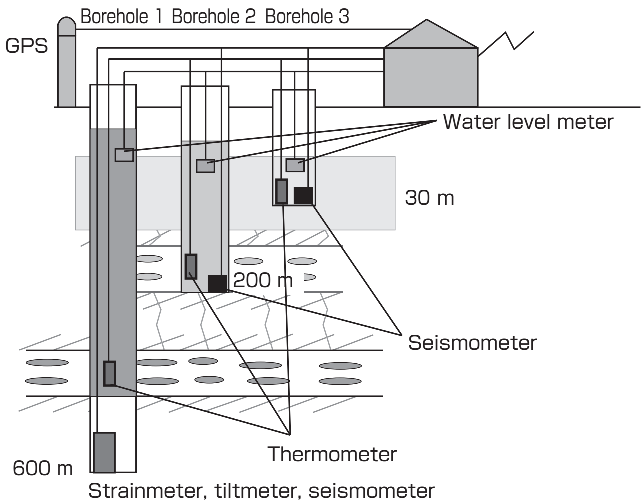

Fig. 8 Typical observation system at N1-N16 observation stations (Fig. 1)

In the deeper extension of the assumed focal region of the Tokai,Tonankai and Nankai earthquakes, the short-term slow slip event very similar to the expected pre-slip is known to occur several times a year with the deep low-frequency tremors,[24][25] which are earthquakes that occur at depth of 30−40 km near the plate boundary. The tremors emit weak lower-frequency waves than ordinary earthquakes do and have unclear beginning and end. Accurate understanding of the spatiotemporal distribution of the slow slip events is important to improve the forecast accuracy of the Tokai, Tonankai, and Nankai earthquakes.[26] If the short-term slow slip expands to the assumed focal region, it is possible to induce the main earthquake. Moreover, when the stress concentrates in the focal region and the occurrence of the main quake approaches, it is estimated by simulation that change in the stress conditions in the deep extension of the focal region will cause change in the occurrence pattern of the short-term slow slip events.[27] AIST monitors the short-term slow slip events and the tremors in cooperation with the National Research Institute for Earth Science and Disaster Prevention (NIED) and JMA. AIST has already found the spatiotemporal distribution of the short-term slow slip events[28][29] in the Kii Peninsula that was not well known before, and AIST's high-sensitive monitoring of the tremors found some interesting results.[30] AIST also investigates how groundwater changes due to the short-term slow slip events. Actually, some changes in confined groundwater pressure were already detected in association with the short-term slow slip event in some observation stations[31] although they were within the range expected from the volumetric strain changes due to the slow slip events. Any changes in the unconfined groundwater level due to the short-term slow slip event have not been detected. Therefore we have not been able to clarify the mechanism of the preseismic groundwater level decrease in the past Nankai earthquakes. The graphs of these observation data are publicized at http:/www.gsj.jp/wellweb/ and they are updated daily.

5 On the attempt overseas to apply the earthquake prediction research based on observation of groundwater

The devices for observation of crustal deformation are generally expensive, and there are many countries and regions where the crustal deformation observation is insufficient although their seismic risks are high. The Southeast Asian countries are such examples. However, groundwater is usually observed in such countries for reasons other than earthquake prediction. By selecting the observation wells under conditions that they are not affected by rainfall, not affected by artificial pumping around them, and have high volumetric strain sensitivity, a groundwater level observation network can be created for observation of crustal deformation. It means that we can create a "simple" crustal deformation (volumetric strain) observation network in a short period. This will enable the application of the "system for detecting preseismic changes in groundwater levels" to such regions. By reviewing the past groundwater level changes related to earthquakes using the volumetric strain sensitivity, it becomes possible to estimate the volumetric strain changes before and after the past earthquakes. From the above, it is thought that this method can contribute to the earthquake disaster mitigation at low cost. Based on such an idea, we started a joint research of "Hydrological and geochemical research for earthquake prediction in Taiwan" with the National Cheng Kung University, Taiwan in 2002.[32] The earthquake and active fault researches including the research for earthquake prediction have been active in Taiwan since 2001. It is because Taiwan suffered massive damage by the Chi-Chi Earthquake (moment magnitude 7.6) that occurred in western Taiwan in 1999.

In the joint research that has been continued for about 10 years, we obtained good results on the mechanism of groundwater change accompanying the 1999 Chi-Chi Earthquake,[33][34] constructed the groundwater observation network consisting of 16 stations to study the earthquake-related groundwater changes and analyzed groundwater changes during and after the earthquakes using the data from this network.[35] On the other hand, the evaluation of S/N is a major issue, since many of the wells of the network are still affected by artificial pumping. By conducting the technological transfer of the "system for detecting preseismic changes in groundwater levels" in Taiwan, the human resources can be trained, and these will contribute to the prevention of earthquake disasters in Taiwan. Besides, the seismicity is more active in Taiwan than in Japan, and annual crustal deformation in some places in Taiwan is more than 10 times larger than in Japan. Therefore, the observation data for groundwater changes related to earthquakes and crustal deformation can be accumulated at a shorter time than in Japan. Therefore if the observations and researches of groundwater changes in relation to earthquakes and crustal deformation are continued, research results can be obtained efficiently. This joint research, which may yield benefit for both Japan and Taiwan, should be continued. In the future, we would like to contribute to the earthquake disaster mitigation in many of Southeast Asian countries.

6 Thinking about the earthquake prediction research after the 2011 Off the Pacific Coast of Tohoku Earthquake

In the research in which the place, magnitude, and time of an earthquake are estimated beforehand to mitigate earthquake disaster, our forerunners used the strong word "prediction" rather than "forecast" (e.g. Imamura (1929)[36]). This was because they aimed at "forecasting with high accuracy" that leads directly to disaster preventing actions before the earthquake. Yet, in fact, the researchers involved in earthquake prediction have been researching "earthquake forecasting" and have struggled to increase its accuracy.[37] As one of the results, long-term earthquake forecasting is now in operation in Japan.[38] However, the magnitude of the 2011 Off the Pacific Coast of Tohoku Earthquake became 9 that surpassed the magnitude ever assumed for this area by earthquake researchers, and about 20 thousand people were dead or missing mainly by the tsunami. It showed that our level of forecasting was still far from prediction.[39] In the region off the coast of middle Sanriku, data were scarce and evaluation could not be done, and in the region off the coast of Fukushima Prefecture, the possibility of occurrence within 30 years of a M7.4 earthquake was estimated to be 7 % . However, in the region off the coast of northern Sanriku, Miyagi Prefecture, and Ibaragi Prefecture, the possibility of occurrence within 30 years of a M7-7.5 class earthquake was estimated to be 80 % or greater.[40][41] Therefore it can be said that the place and time in the long-term earthquake forecasting was approximately correct. Particularly in the region off the coast of Miyagi Prefecture, the possibility of occurrence within 30 years of a M7.5 class earthquake was kept at 99 % in 2011 for alert although a M7.2 earthquake occurred in this region in 2005. It was because the GPS observation results[42] were considered to show that the energy had not been completely dissipated in the assumed focal regions. The figure of 99 % was the maximum figure of all the long-term forecasts by the Headquarters for Earthquake Research Promotion. Therefore, some factors could be positively evaluated from the perspective of science and disaster prevention in forecasting this earthquake, and the criticism that “the research for earthquake prediction (forecasting) is useless” is not valid. We should thoroughly conduct scientific evaluation and review of the forecasting of the 2011 Off the Pacific Coast of Tohoku Earthquake, and continue the earthquake prediction research.[43]

7 Conclusion

As a *Type 2 Basic Research*, we constructed a system for detecting preseismic changes in groundwater levels that uses a combination of long-term observation and analysis of groundwater, a poro-elastic theory, and the Tokai earthquake prediction model suggested by JMA. The outcome is our contribution to the national project for prediction of the Tokai earthquake. To apply the system to Tonankai and Nankai earthquakes, we constructed an integrated groundwater observation network in and around the Shikoku and the Kii Peninsula. This network is now being used to observe and study groundwater and crustal deformation. Since 2002, we have also been carrying out international cooperative hydrological research for earthquake prediction in Taiwan to help minimize the damage caused by earthquakes in Southeast Asia. Since seismic activities are higher and crustal deformation is larger in Taiwan than in Japan, we can learn about the relationship between earthquakes and groundwater more efficiently. This cooperative research is also expected to improve the system. We underestimated the magnitude of the 2011 Off the Pacific Coast of Tohoku Earthquake, which was one of the factors that brought the severe damage in and around the Tohoku area. However the long-term forecast of the place and time of the earthquake can be considered to be fairly accurate. Therefore, we should examine scientifically the reasons for the underestimation, and advance earthquake prediction research.

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Postscript

After this paper was written and accepted, the Seismological Society of Japan (SSJ), of which the author is a member, released the action plan for the various issues that were raised by the 2011 Off the Pacific Coast of Tohoku Earthquake (http://www.zisin.jp/pdf/SSJplan2012.pdf). In this document, the use of the terms "earthquake prediction" and "earthquake forecasting" are strictly defined. Conventionally, the term "earthquake prediction" had been also used widely for "forecasting beforehand the specific place, magnitude, and time of the earthquake that may occur." However this was sometimes confused with the earthquake prediction in the narrow sense that leads to warning and it generated the excessive expectation of society for preseismic "warning." As a reaction, the earthquake researchers were criticized heavily after the 2011 Off the Pacific Coast of Tohoku Earthquake. Therefore, the SSJ decided to distinguish the terminologies by defining earthquake forecasting as "forecasting beforehand the specific place, magnitude, and time of the earthquake that may occur," and earthquake prediction as the accurate earthquake forecasting that actually leads to warning. The SSJ also re-emphasized that earthquake prediction is extremely difficult at present. However, as mentioned in chapter 6, if the accuracy of earthquake forecasting is raised, it will become earthquake prediction in the narrow sense, and therefore it seems difficult to differentiate the earthquake prediction and forecasting clearly at the research level. Since the "strict definition of earthquake prediction and earthquake forecasting" has been discussed in the SSJ, I consciously tried to distinguish the usage of the terms in this paper: those that lead immediately to warning (earthquake prediction) and those that do not (earthquake forecasting). However, there is no clear-cut distinction.

In the earthquake at L'Aquila, Italy (occurred April 6, 2009; M6.3; over 300 people dead), seven people including six scientists were charged for issuing the "statement of safety" prior to the earthquake. This was an incident that illustrated the difficulty of earthquake prediction. However there are research topics that must be tackled even if they seem insurmountable. The author thinks that earthquake prediction is one of those topics in earthquake-prone Japan.

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Discussions with Reviewers

1 Overall comment

Comment (Eikichi Tsukuda, AIST and Hideto Taya, AIST)

This is an excellent research paper that describes the development of the relationship between earthquake occurrence and groundwater level accompanying crustal deformation with theoretical foundation (poro-elastic theory) in the background, and long-term groundwater level observation and analysis at the core. It addresses the processes of the construction of groundwater observation system and the prediction of the Tokai, Tonankai, and Nankai earthquakes through the organization of such an observation network. As the imminent threat increases for the Tokai, Tonankai, and Nankai earthquakes and with the experience of the Great East Japan Earthquake or the 2011 off the Pacific coast of Tohoku Earthquake, the social interest in this field is increasing. Since human damage can be effectively mitigated if the earthquake prediction information is released, the progress of this research draws high expectations. On the other hand, long-term observation must be continued before any results can be obtained, and it is apparent that this responsibility must be borne by the public research institute. I think this is a difficult challenge as a *Full Research*.

2 Volumetric strain caused by tides

Question (Hideto Taya)

I have a question about the "volumetric strain" caused by tides. You mention that "the scale is about 10^{-7}" in Japan, but is this determined by latitude of the earth?

Answer (Naoji Koizumi)

The maximum amplitude of ground deformation by the earth tides is determined approximately by latitude.

3 Earthquake prediction by groundwater level observation

Question (Hideto Taya)

Earthquakes occur throughout Japan, but I think their mechanisms differ for each occurrence. With this understanding, which earthquakes are predictable by groundwater level observation?

Answer (Naoji Koizumi)

At the moment, the predicable earthquakes are the subduction-zone types where the pre-slip scenario can be applied. In the future, if a quantitative, preseismic crustal deformation scenario is presented for the other types based on a reliable model, earthquake prediction by the groundwater level observation can be used for them as well.

4 Assumption of the new mega-earthquake and the observation system for it

Question (Eikichi Tsukuda)

The government has already forecasted damage due to the assumed earthquake of magnitude 9. Can you comment in relation to your observation system? This is much greater than the previously assumed magnitude. Is there any effect on the current observation based on the new assumed model?

Answer (Naoji Koizumi)

For the M9 class mega-earthquake that is newly assumed to occur in the Nankai Trough, the focal region expanded west (to Hyuganada), and new observation stations may be needed in Kyushu. The focal region expanded far off the coast cannot be monitored by land observation. Therefore cooperation with the ocean floor observations by the Japan Agency for Marine-Earth Science and Technology, JMA and others will be necessary. Also, since the assumed model changed greatly, it will be difficult to interpret the observation data and to forecast the earthquake based on those data.

5 Observation and international joint research for prediction research of infrequent giant earthquakes

Question (Eikichi Tsukuda)

The interval of earthquake occurrence in a certain region is at least 100 years, and this is significant longer than the lifespan of the researcher. I think this inhibits the dramatic scientific advancement in seismology through hypothesis and proof. International joint research may be one method to overcome this. I think there can be efforts to gather overseas case studies other than those of Taiwan. What do you think? Can you also comment on the recent overseas case studies on the earthquake occurrence process (preparatory process)?

Answer (Naoji Koizumi)

For the observation and research of the earthquake-related groundwater changes, we have also been working with the U.S. Geological Survey. It is true that more international cooperation will be necessary in the future and I would like to continue the effort.

The overseas cases where the pre-slips were possibly detected in the postseismic analysis are: the 1960 Great Chilean (Valdivia) Earthquake (M9.5), the 1997 Kamchatka Earthquake (M7.8), and the largest aftershock (M7.6) of the 2001 Peru Earthquake (M8.4). Japanese cases are: the 1944 Tonankai Earthquake (M7.9), the 1946 Nankai Earthquake (M8.0), the 1964 Niigata Earthquake (M7.5), and the 1983 Sea of Japan Earthquake (M7.7). For the 2011 Off the Pacific Coast of Tohoku Earthquake, the possibility that pre-slips might have occurred was indicated from the observation of the ocean floor tsunami meter and the movement of seismic activities immediately before the earthquake. However, there was probably no acceleration of the slip that is expected in the pre-slip of Tokai earthquake. From these results I think the conventional model will be revised or new models may be proposed for the earthquake occurrence process. There is a close relationship between the improvement and creation of models and accurate observation data. We would like to keep accurate observation and analysis to provide appropriate restraint conditions for the models. We would also like to continue gathering the research results on the earthquake occurrence process in Japan and overseas.

6 JMA's volumetric strainmeter and groundwater observation

Comment (Eikichi Tsukuda)

It can be read that groundwater observation is not necessary if we have the JMA's strainmeter. I think you should carefully explain the characteristic of the groundwater data and its complementarity to the other data.

Answer (Naoji Koizumi)

As was explained in this paper, the strain detection accuracy of the groundwater observation estimated from the noise level is about the same or slightly inferior compared to the strainmeter. However, considering that the price of the groundwater observation devices such as the water level meter is about one-tenth to one-hundredth compared to the strainmeter, I think groundwater observation is superior in terms of cost performance. Even in countries and regions where the expensive crustal deformation observation devices such as the strainmeter are not affordable, there are many places where groundwater level is observed. Therefore the groundwater observation can be used universally as a method of earthquake prediction. In addition, since the strain observation and groundwater observation are independent, if both data can be explained by a single physical model such as the pre-slip model, then that will increase the reliability of the physical model and the forecasting based on that physical model.

7 Social risk of earthquake prediction research by groundwater observation

Comment (Eikichi Tsukuda)

As stated in the paper, the groundwater is relatively easily observed and closely related to everyday life. Therefore, there have been many reports of preseismic groundwater anomalies by the general public, and there is danger that the circulation of civilian information with poor accuracy or incorrect information may arouse social unrest. In such cases, the scientific observation data over a long term are important. Therefore the social responsibility of AIST groundwater observation is heavy. I think cooperation with JMA is necessary. Can you comment on AIST's expected response?

Answer (Naoji Koizumi)

As you indicate, I think the circulation of incorrect information on earthquake prediction can be prevented by showing the properly managed, accurate groundwater observation data. Therefore, we publicize the graph of the observation data. For the research results on earthquake-related groundwater changes, we conduct active outreach activities using programs of Open Houses of AIST and dispatch lectures of AIST. We not only provide JMA the observation data and analysis results but share various information and analysis methods on earthquakes with JMA. When we receive inquiries from JMA about abnormal groundwater changes, we provide information on how to interpret them appropriately.

It is important that the disaster prevention personnel of the local government are able to correctly interpret the various data and models about earthquakes from various sources and make proper decisions to prevent social confusion. From this perspective, we offer the "training program on earthquake and tsunami for local government personnel" for the people in charge of disaster prevention in the local governments of the places where our groundwater observation stations are located.