Water-Level and Stream-Flow Earthquake Precursors and Their Possible Mechanisms

Chi-Yu King[1]

[1]Retired

November 21, 2022

Abstract

This paper presents some pre-earthquake and coseismic water-level and stream-flow changes observed in Japan and Taiwan. The results suggest that: (1) Hydrological precursors do occur; (2) they can be observed at a relatively few sensitive sites; (3) these "sensitive" sites consistently show coseismic changes; (4) the mechanisms of these precursors can be understood, if crustal heterogeneity and pre-earthquake slow-slip events are included in their mechanism consideration. In Japan, the monitored well was sensitive, because it tapped a permeable aquifer connected to a nearby fault, which was under a hydraulic –pressure gradient caused by pumping activity in an underground gallery on the other side of the fault. Also, the fault was in a near-critical condition, such that leakage could be caused by a small crustal disturbance, such as seismic shaking, in the case of coseismic changes, or a stress increment, in the case of precursory changes. In Taiwan, both the sensitive well and the stream gauge were located on the hanging wall of the seismogenic fault of the magnitude-7.6 Chi-Chi earthquake in 1999. The hanging wall probably bulged before the earthquake, causing opening up of fractures along some secondary faults, and allowing stored groundwater to flow down to the monitored stream and caused the observed pre-earthquake stream-flow increase. The continued fracture-opening process toward greater depth then caused down-flow of water into greater depth of the crust and triggered the occurrence of slow-slip events, which propagated down-dip to where these faults met the seismogenic fault and caused slow-slip events to propagate up-dip the seismogenic fault toward the hypocenter, triggering the earthquake and the observed water-level precursor at a well located near the tip of the wall.

Water-Level and Stream-Flow Precursors to Earthquakes and Their Possible Mechanisms

By Chi-Yu King

Earthquake Prediction Research Inc.

El Macero, CA 95618 USA

Abstract

This paper reviews two cases of hydrological precursors observed in Japan and Taiwan, and presents a detailed discussion on their mechanisms. The case in Japan is water level recorded at a "sensitive" well that showed 5 pre-earthquake drops before 5 large earthquakes of magnitudes 6.1-8.1 at distances of 220-1260 km, and a large and 6-month-long precursory drop before a rare local earthquake of magnitude 5.8. The water level also showed many co-seismic drops. The high sensitivity of the well is attributed to its tapping a permeable aquifer which is connected to a nearby fault that contains a layer of normally impermeable fault gouge under a large hydraulic-pressure gradient and in a nearly critical crustal-stress condition. The well is situated on the higher-pressure side of the fault, such that any earthquake-related or artificially-caused fissure occurrence in the gouge layer may result in a leak of water to the other side of the fault, and thus a water-level drop. The observed pre-earthquake drops are attributed to crustal-stress increments associated with the occurrence of slow-slip events before the earthquakes. The coseismic drops are attributed to water leakage of both the fault and the tapped aquifer by seismic shakings. The sensitivity of the well appears to be variable, being especially high during a 6-months period before the rare magnitude 5.8 local earthquake and lower during the following year.

The case in Taiwan is a stream-flow change and a water-level change recorded shortly before the magnitude 7.6 Chi-Chi earthquake in 1999. Both changes were recorded near the epicenter on the hanging wall of the seismogenic thrust fault. The stream-flow change (a pre-earthquake increase followed by a coseismic decrease) is attributed to a sequence of events: Crustal-bulging; tensile fractures in the ground starting from the surface at higher elevation and then to greater depths; groundwater flowing down from the stream banks to the stream, then from the stream to the crust below; occurrence of slow-slip events under critical shear stress; and the water-level precursor and the earthquake triggered by slow-slip events.

Based on the present study, we may suggest that: Hydrological precursors do occur; they can be observed at a relatively few sensitive sites, which are usually located along fault and fracture zones, preferably on the hanging wall, if a thrust fault; and these sensitive sites show coseismic changes also. To understand the earthquake-related changes, we need to include crustal heterogeneity and pre-earthquake slow-slip events into consideration.

Introduction

Earthquakes is a well-known major natural hazard that has ruined numerous lives and properties in many parts of the world. One important way to reduce earthquake hazard is to accurately predict their occurrence time, location, and size, especially in short terms (several days in advance). Earthquake prediction is a scientific dream, which had been hotly pursued since 1960s by many scientists worldwide until late 1990s, when it was found to be too difficult to achieve. As a result, most scientists involved in earthquake studies today consider earthquakes to be unpredictable, and devote their efforts to other aspects of earthquake mitigation, such as long-term probabilistic forecast and building reinforcement, leaving prediction to be still the greatest challenge in earth science. Some efforts have continued, however, and have found various creditable pre-earthquake changes, recorded by geophysical and hydro-geochemical instruments located on ground, in space, and at the sea bottom in many seismic regions. Such changes include anomalies in geomagnetic field, ionospheric total electron content, water level/chemistry, streamflow rate, and soil-gas chemistry (Ouzounov, et. al, 2018; King and Manga, 2018; King, 1986). Also, with an increasing number of geodetic instruments, such as GPS both on satellites and on the ground, deployed during the past 20 some years in Japan and elsewhere since about 2000, it has been found that faulting in the form of slow-slip events occurs frequently in many seismic regions, especially many subduction zones. These previously neglected events, may cause stress redistribution along fault zones and trigger major earthquakes, their foreshocks, and short-term earthquake precursors (e.g., King 2018; King and Chia, 2018). All such recent developments suggest that some earthquakes may be predictable and that a renewed effort toward earthquake prediction may be desirable.

There are several reasons why earlier research efforts failed to discover earthquake-precursors. Beside the inherent difficulties of earthquake's being possibly a self-organized-critical phenomena and the inaccessibility of earthquake source for direct measurement, any geophysical and hydro-geochemical data recorded by scientific instruments is always affected by many environmental variables, such as rainfall, tidal variation and barometric-pressure changes. Well-funded earthquake research has mostly been seismological and geodetic in nature, together with some theoretical and laboratory model studies; very little funding has been provided for studies in other disciplines, such as geochemistry and electromagnetic physics. Also, there has been a lack of realistic crustal models to guide proper instrument deployment and data interpretation.

The current theoretical models usually assume the earth's crust to be homogeneous, isotropic and elastic/poroelastic; they do not take proper account of the crust's heterogeneity, its multiphase (solid, liquid and gas) nature, and the existence of various defects, such as faults and fractures of different sizes. As a result, many reliably observed earthquake-related hydrological, geochemical and geophysical changes are left without explanation. For example, earthquake-related hydro-geochemical changes were commonly recorded only at a few so-called "sensitive sites", even located much farther away from the epicenter of an earthquake than what the models have anticipated, but not at many other sites, even though they are much closer to the epicenter (e.g., Rojstaczer and Wolf, 1992; Silver and Vallette-Silver 1992; Hill, et al. 1994; King et al. 1994; Kitagawa and Koiaumi, 1996; King 1998).

This paper gives a brief review of two cases of hydrological precursors observed in Japan and Taiwan, and a detailed explanation for their mechanisms.

The case in Japan

The case in Japan provides an ideal opportunity to study earthquake-related water-level changes and to understand their mechanisms because of several reasons: The hydrogeological condition of the monitoring site is well known, the local seismicity was high, high-quality water-level data has been recorded for a long period of time at 16 closely clustered wells of different depths in the vicinity of a fault that was subjecting to hydraulic-pressure gradient, many different coseismic and pre-earthquake changes were recorded, and artificially caused changes by a pumping test and a leak test were recorded for comparison.

This monitoring site is in Tono Mine, which is located within a relatively stable crustal block bounded by several active faults in central Japan, where 4 tectonic plates meet. Here, as shown in Figure 1, the Pacific plate in the east subducts westward beneath the North American plate along the Japan trench in the north, and beneath the Philippines-Sea plate in the south; the Philippine-Sea plate subducts northeastward beneath the North-America plate along the Sagami trough and northwestward beneath the Eurasian plate along the Nankai trough, (Ishida, 1992) .

(A) Observation of coseismic and pre-earthquake water-level changes

Water level recorded at a sensitive well in Tono during the study period of 1989-98 showed many coseismic drops and 5 pre-earthquake drops before 5 large distant earthquakes; it also showed a large and long pre-earthquake drop before a rare local earthquake of magnitude 5.8. These changes are not caused by rain fall or barometric-pressure changes. (King et al. 1999, 2000)

Figure 1 shows the location of the well in Tono mine (triangle) and these earthquakes (dark beach balls) among other earthquakes of magnitude 6.0 or larger (shaded beach balls). They include the magnitude 7.2 Kobe earthquake in 1995 and a magnitude 8.1 earthquake in 1994 near Hokkaido. Figure 2 is an enlarged map, showing the location of all local earthquakes of magnitude 4 or larger during the same period, including a rare magnitude 5.8 on 16 March 1997 (97/3/16) about 50 km away.

Figure 3 shows the observed coseismic changes recorded at the sensitive well, SN-3. All of these changes have a similar shape, a sudden coseismic drop followed by a gradual recovery lasting about a week, regardless of the location or mechanism of the earthquakes. King, et al. (1999, 2000) suggested that this shape is a characteristic of the monitoring site: The the sudden drop is caused permeability increase of the aquifer-fault system tapped by the well, and the recovery by the self-healing process of the system. Also, they noticed that the earthquakes that caused water-level changes usually were larger and closer to well, with an estimated coseismic strain greater than about $5x10^{8}$, but the amplitude of the coseismic drops does not have such a correlation (Figure 3b of King et al. 1999). Thus, they suggested that the permeability increase is not controlled only by the intensity of seismic shaking, but also by such local condition as pre-existing stress level.

Fig. 4 shows the coseismic water-level change at SN-3 for the rare local magnitude 5.8 earthquake (first local event of magnitude larger than 5 since 1983) on March 16, 1997 about 50 km to the southeast at a depth of 39 km. This change consists of a sudden drop that began about 20 s after the earthquake followed by a gradual recover that began 3 hours after the earthquake. A feature that is different from the other coseismic changes is that the "recovery" is much longer and larger (180 cm) than the drop (60 cm), as shown on a compressed vertical scale in Figure 4.

A similar water-level change was recorded at a less sensitive SN-1 well, which is 91-m-deep and only 80 m away from SN-3 (Figures 7 and 8). The coseismic drop at SN-1 for this earthquake has a smaller amplitude and slower response, beginning 5 hours after the earthquake with a recovery beginning 3 days after the earthquake. Shown in Figure 4 are also the coeismic changes recorded at multiple depths (with the help of packers) of two newly drilled wells TH-7 and TH-8, where water-level monitoring began only several days before the earthquake. These results will be discussed later.

The above-mentioned feature of unusually large and long "recovery" for the rare local earthquake was puzzling at first. But when the long-term record was plotted, it became understandable: The "recovery" (indicated by an arrow in 1997) actually consists of two parts, a coseismic drop coincided with a precursory drop that began 6-month earlier in September 1996!

Figure 5 shows the long-term water-level record at SN-3 and SN-1 for the entire period of observation during 1989-99 together with corresponding rainfall record. The water-level curves are broadly similar, showing large changes that are not significantly influenced by rainfall. As pointed out by King et al. (2000) and discussed later, most changes are attributable to water leaks through a nearby fault zone, whether caused by earthquakes or human activity. The water-level at SN-3 shows not only this 6-month-long drop but also five smaller pre-earthquake drops (indicated by 5 arrows earlier in Figure 5). These drops coincide in time with 5 large distant earthquakes, and their dates, magnitudes, and epicentral distances are given in the following chronological order: 1990/ 9/24, 6.6, 290 km to the southeast; 1994/10/4, 8.1, 1257 km to the northeast; 1994/12/28, 7.5, 800 km to the northeast; 1995/1/17, 7.2 (Kobe) to the west, 219km; 1996/9/5, 6.1, 509 km to the southeast. Except the Kobe earthquake, they are all located along the subduction zones, the farthest being the magnitude 8.1 earthquake 1257 km away near Hokaido, and the nearest the magnitude 7.2 Kobe earthquake 219 km to the west.

As pointed out by King et al (1999, 2000), these coseismic and pre-earthquake changes cannot be explained by the poro-elastic dislocation models, and require permeability changes at the monitoring sites. The gradualness the pre-seismic drops suggests that they were caused by some gentler cause than seismic shaking. The pre-earthquake changes are not recorded at the less-sensitive well SN1, which is only 80 m away from SN-3, although both curves are broadly similar (Figure 7).

The smallest among the 5 earthquakes that showed pre-earthquake changes at SN-3 occurred on September 5, 1996; it is relatively small (magnitude of 6.1) and far away (510 km), and should not have caused the pre-earthquake change normally. King et al. (1999) attributed this anomalous occurrence to heightened sensitivity of the SN-3 well at a time when the local stress was critically high before the magnitude 5.8 local earthquake. Actually, in the whole region of central Japan, the crustal stress may have already reached a near-critical level as early as 1990, as evidenced by the occurrence of the 1990 magnitude 6.6 earthquake, the 1995 magnitude 7.2 Kobe earthquake, the 1996 magnitude 6.1 earthquake, and the rare 1997 magnitude 5.8 local earthquake, all in this region. However, for nearly a year after the magnitude 5.8 earthquke, no significant earthquake-related water-level change was observed, even when a magnitude 5.9 earthquake occurred on May 24, 1997 about only 100 km away to the south (Figure 2). King, et al. (1999) suggested this result to be due to a temporary sensitivity decrease at SN-3. The sensitivity apparently recovered by February 10, 1998, when a coseismic drop was recorded for a magnitude 4.3 earthquke about 35 km away. Similar sensitivity variation was reported previously by Wakita (1996) for a well, where radon content of groundwater was monitored.

Figure 6 shows the above-mentioned pre-earthquake water-level changes on an expanded time scale. They have similar shape to each other, beginning with a gradual drop of about one week long, followed by a gradual recovery lasting about a week. The pre-earthquake changes have much larger amplitude than the corresponding coseismic changes (some of them are discernable in Fig. 6) and last longer, indicating that they involve a slower source and a larger water loss from the well. However, the rate of recovery is comparable to that of the coseismic changes.

(B) Understanding of the observed water-level changes

To understand any earthquake-related water-level changes, we need to know the hydrogeological condition of the monitoring site in detail. The site in this study is in Tono mine, where the largest known uranium deposit in Japan is located, and there was no actively mining activity during the study period owing to the lack of demand for domestic uranium. The study area is traversed by a reverse fault, named Tsukiyoshi, in the east-west direction (Figure 7). The fault has dip angle of 60-70^0 to the south and an offset of 30 m (Figure 8). It consists of a weak, pliable and ordinarily impermeable fault-gouge zone about 10-30 m thick sandwiched between two fracture zones of high permeability, each several meters thick (Koide, et al. 1997). The fault is under a north-south tectonic compression related to the Nankai subduction zone to the south. On the south side of the fault, there is a 126-m deep underground gallery, from which the inflowing groundwater was continuously pumped out at a rate of 50 t per day in order to keep the gallery dry. The pumping activity had decreased the water pressure on the south side while leaving the pressure on the north side almost hydrostatic, thus creating a considerable hydraulic-pressure gradient across the fault. One branch of the gallery crosses the fault, where the fault structure may be examined.

Water-level data was continuously recorded during 1989-99 at 16 wells of different depths closely clustered within 400 m of the Tsukiyoshi fault; most of them, including the sensitive well SN-3, are located on the higher-pressure north side (Figure 7). SN-3 is 131-m deep and 80-m apart from the 91-m-deep SN-1 well. SN-3 tapped a highly permeable aquafer about 30-40 m thick, which is the weathered top layer of the basement rock, Toki Granite (TG, in Figure 8). The aquafer is connected to the fault, which is normally impermeable, sustaining a large pressure difference (Fig. 8) (Sugihara, et al. 1991). Thus, water-level drop at SN-3 may be attributed to water leakage through the aquafer-fault system, and recovery of the drop to self-sealing of the system.

The suddenness of the observed coseismic water-level drops can be attributed to the violence of seismic shaking, which is enough to open up fissures not only in the fault-gouge but also in the tapped aquifer itself. The gradualness of precursory drops, on the other hand, suggests that the fissures probably opened only in the fault-gouge layer in response to a slower source. But, since the amplitudes and duration of pre-earthquake drops are larger than the coseismic drops, the associated extent of fault-zone leakage and amount of water loss from the aquifer are probably much larger than those associated with coseismic drops. King, et al. (1999, 2000) suggested that the precursory drops might be caused by some episodic, broad-scaled, low-amplitude incremental crustal deformation, but they did not know what process might have caused such a deformation. Since then, however, many geodetic instruments have been deployed in Japan and elsewhere, and many slow-slip events have been detected as a result, especially along the subduction zones worldwide. Some of such events occurred before and near large earthquakes. These so-called “pre-slips” may have redistributed the crustal stress along the fault zone and triggered the corresponding earthquakes (Kato, et al. 2012). Based on this recent discovery, King (2018) suggested that the required slow tectonic deformation may have been caused by some slow-slip events.

Indeed about 15 years later, Kobayashi (2014) reported that a magnitude 6.7 long-term slow-slip event had occurred at Kii Channel, which is not too far away from Tono, beginning in early 1996 and lasted for about 1-1.5 years. This event may have shifted the crustal load toward the Kii and Tono vicinity after the occurrence of the 1995 Kobe earthquake, and provided the necessary crustal-stress increment needed to trigger the above-mentioned series of events, including the magnitude 6.1 earthquake in 1996 and its water-level precursor as well as the magnitude 5.8 local earthquake and its 6-month-long precursor (Figs. 5 and 6). During this 6-month period, increased water flow was observed at the KNA2 hole in the gallery, and the flow could not be stopped despite of several attempts. Yet at the end of this period, immediately after the magnitude 5.8 earthquake, water flow at KNA2 returned to normal automatically. These observations all suggest that the 6-month long water-level drop is a precursor to the magnitude 5.8 earthquake, according to King et al (1999 and 2000).

The water level at SN-1 was not sensitive to the shorter-term coseismic changes and pre-earthquake changes; it showed only a 6-month long drop prior to the magnitude 5.8 local earthquake and a 120-day drop caused by a leak test (Figure 5). Also, it is slow in response, beginning to recover about 3 days after SN-3, in both the cosismic and the leak cases. What made the difference between these two neighboring wells, 80 m apart (Figure 7), is that SN-3 tapped a permeable aquifer but SN-1 did not (Figure 8). The observation cannot be explained by poro-elastic models for the crust; it requires consideration of crustal heterogeneity and permeability changes at the monitoring site.

In addition to SN-3 and SN-1, water pressure was monitored at 5 different depths (with help of packers) in two 200-m-deep wells, TH-7 and TH-8, beginning in mid-March 1997. These wells are located about 140 m and 80 m to the south and north of the fault, respectively. Both of them at their lowest levels tapped the same permeable aquifer in Toki Granite (TG), but the aquifer is offset by about 30 m by the fault and thus are not connected with each other (Figure 8). At the depths of this aquifer, they are both about 110 m away from the fault plane (see Fig. 7). But their earthquake-related water-level changes differ greatly in pattern. For the magnitude 5.8 local earthquake, the changes recorded in TH8 on the north side exhibit a similar shape as at SN-3, namely, a sudden drop followed by a gradual recovery, though with a faster response because it is closer to the fault. However, the shape of water-level change recorded at TH-7 on the south side of the fault is quite different; it showed a small delayed surge about 1 day after the earthquake, followed by a gradual increase (bottom curve for TH-7 in Figure 4). This sharp contrast shows the effect of hydraulic-pressure difference between the two sides of the fault, confirming the assertion that the shape is a monitoring-site effect, not an earthquake-source effect, as discussed by King et al. (1999).

The hydraulic pressures measured in the basement-rock levels were in the range of 0.190-0.745 MPa in TH-7 and 0.968-1.505 MPa in TH-8 (Figures 5b and c of King et al. 1999), with an average pressure difference of about 0.7 MPa.

King et al. (1999) conducted a pumping test and a leak test in order to further understand the mechanisms of the observed water-level changes. The pumping test was conducted in November 1997 at a newly drilled 97FT-01 well, which is 167m deep and about 70 m and 25 m from SN3 and SN-1, respectively. By pumping water-level down by as much as 48 m in this well for several days, only about 5 cm water-level drop was recorded at both SN-3 and SN-1. This drop is quite small, almost invisible in the long-term record (Figure 5), indicating a low vertical permeability between aquifers in the vicinity of these wells, which are far away enough from the fault zone.

The leak test was done for a period of 120 days, beginning on June 19, 1998 by opening up the cap of an 80-m-long slant KNA-2 hole in the 126-m-deep gallery on the south side of the Tsukiyoshi fault. This hole penetrates the fault to where the permeable aquifer tapped by SN-3 meets the fault on the north side (Figures 7 and 8; see also Figure 4 of King et al. 1999). At the uncased bottom of the hole, two interconnected packers were used to isolate a section, from which the groundwater in the aquifer was drained for continuous geochemical monitoring. The packers were normally kept inflated by pressurized nitrogen from a supply tank. But twice in 1994 the packers failed (the pressure dropped to zero, as shown in Figure 7 of King et al. 2000), and the failure coincided approximately in time with the 3 pre-earthquake water-level drops during 1994-95 (see Figure 5 and middle 3 curves in Figure 6). At about the same time, water-flow increase from KNA2 hole was observed in the gallery. These observations raised the possibility that the observed water-level drops were not earthquake related, but were caused by increased outflow of water from the hole as a result of packer failure. To check whether packer failure at KNA2 could affect water level at SN-3 and SN-1 wells, King et al. (2000) conducted the leak test, and they found that the water-levels at SN-3 and SN-1 began to drop about 9 hours and 4 days after the opening of the cap of the hole, respectively (Figure 5; Figure 9a of King et al. 1999). The rate of water-level drop at SN-3 was initially comparable to the rate of water-level drop that occurred at the end of September 1994, 10 days before the earthquake on October 4, 1994 (second curve in Figure 6), but was slightly smaller afterwards. Thus packer-related increase in flow rate at KNA2 can account for only part of the water-level drop observed in September 1994. The same conclusion can be drawn also from the water-level recovery rate for this earthquake. Thus, King et al. (2000) concluded that both the pre-earthquake water-level drops and the packer failure were due to fissure occurrence in the fault-gouge layer of the fault zone caused by some low-amplitude and broad-scaled slow tectonic deformation before these earthquakes, and the recovery is by self-healing of the gouge layer. Such deformation may have also caused the previously mentioned leakage at this hole that could not be stopped by several attempts prior to the magnitude 5.8 local earthquake but stopped automatically after the earthquake.

As to the large water-level drops at SN-3 and SN-1 in 1995 (Figure 5), they coincide approximately in time with the water release at another hole, KNA6, in the gallery for chemical analysis by another research group. This 100-m-long hole is approximately parallel to KNA2 and situated about 40 m to its west. The water-level began to drop shortly before the water release began, and began to rise shortly after the hole was permanently sealed. The effect of this release on water levels of the wells, as measured by the drop and recovery rates, was about the same as for KNA2 (King et al. 2000).

The 9-hour delay of water-level drop at SN-3 in the leak test is much longer than those of the coseismic drops. For the magnitude 5.8 earthquake, for example, the water-level began to drop only 20 s after the earthquake, and the drop rate is much higher than the drop rate in the leak test. Since SN-3 is too away from the fault (about 360 m) for the leak of water to begin in 20s, the cosismic leakage probably occurred not only in the fault zone, but also in the aquifer itself, especially around the case of the well. The higher rate of coseismic drop also indicates a more extensive fissure openings in the fault zone than the leak-test case (King et al. 1999, 2000). However, the difference of the recovery rates between coseismic drop and leak-test drop is small. This is understandable however, because both the fault zone and the aquifer were recovering simultaneously.

At the end of the leak test, when the leak was stopped by re-capping KNA-2 hole, the water level at SN3 began to recover about 12 hours later, and proceeded at a rate which is much smaller than the coseismic case. This result also indicates that the postseismic recovery must have involved a more extensive damage of the aquifer/fault system (King et al. 1999).

Toward the end of 1998, the water-levels at SN-3 and SN-1, as well as some other wells, began to drop mysteriously (Figure 5). After investigation, the culprit was found to be another group of researchers, who drilled a hole about 1 km deep and I km away on the south side of the Tsukiyoshi fault (MIU-2 in Fig. 8). The water-levels began to drop about 2 days after the drilled hole reached a depth of about 900 m, where it broke through the fault, causing groundwater to flow out of the hole. When efforts were made to stop the leak at the ground surface, the water continued to flow out of the hole into some shower aquifers. This observation shows that the observed water-levels are affected by water leakage through the fault over a wide area of the fault plane, probably via the highly permeable fractured side zones that sandwiched the fault gouge zone. The rate of water-level drop in this case is smaller than the cases mentioned above for KNA2 and KNA6, which is understandable in view of the longer flow path in the present case. Unfortunately, because of the inability of the group to seal the leak at MIU-2 to maintain the hydraulic pressure difference across the fault, the sensitivity of the SN-3 well has been greatly diminished.

The case in Taiwan

Taiwan is located in a subduction zone, where the Philippine-Sea plate subducts northward beneath the Eurasian plate along the Ryukyu Trench in the north and the Eurasian plate subducts eastward beneath the Philippine-Sea plate along the Manila Trench in the south. The plate convergence rate is about 8 cm/year with a contraction rate of 2.0-4.5 cm/year in the mountainous fold-and-thrust belt of western Taiwan, where the Chi-Chi earthquake occurred (Yu et al. 2001).

The magnitude 7.6 Chi-Chi earthquake, the largest inside of Taiwan in history, occurred at 1:47 am on 21 September 1999 local time (17:47 on 20 September UTC), at the end of a rainy season, with an epicenter at 23:85^{o}N; 120.82^{o}E and a depth of approximately 8 km (Figure 9). The focal mechanism was oblique thrust with a strike of 5^{o}, a dip of 34^{o} and a rake of 65^{o}. Coseismic ruptures, approximately 100-km long, coincide with the surface trace of the north-south trending Chelungpu thrust fault in western Taiwan fold-and-thrust foothills area. GPS data showed a coseismic horizontal offset of 2.4-10.1 m across the Chelungpu fault, and a vertical offset of 1.2-4.4 m. The crustal deformation before the earthquake was essentially a uniaxial compression in the direction of 114^{o} at a strain rate of 0.36 µ/year (Yu et al. 2001). After the earthquake, most nearby buildings on the hanging wall of the fault were seriously damped, while very few on the footwall were, even those located only a few meters from the ruptures (Chen et al. 2000; Dong et al. 2004).

(A) Observation of pre-earthquake stream-flow and water-level changes

Two precursors were observed before the Chi-Chi earthquake (Figure 9): A large stream-flow increase 4 days before at a flow gauge (Figure 10) and a water-level increase 3 hours before at a sensitive well (Figure 11). Both of the monitoring sites were located near the epicenter on the hanging wall (east side) of the seismogenic fault (Figures 9 and 12).

Figure 9 shows the location of the flow gauges (circles), where streamflow was measured daily. They were all in the mountainous area on the east side of the fault, and most of them recorded post-earthquake stream-flow increases, as observed in many other studies (Liu et al. 2018).

The only exception is CS64 (red circle in Figures 9, 10), which was located nearest (4 km) to the epicenter and above the hypocenter, and it recorded a pre-earthquake increase 4 days before the earthquake, followed by a coseismic drop, as shown in Figure 11a (Liu, et al. 2018). The flow increase was very large, 124 m^3/s, but the drop was even larger, 155 m^3/s. Furthermore, the flow rate stayed below the background level for 8 months!

This anomalous change was not observed at a gouge (CS44) located at the base of a dam about 3 km upstream (yellow circle in Figure 10). The gauge at CS44 only recorded a post-earthquake flow increase caused by water release from an upstream reservoir for safety purpose. Thus, the extra amount of water recorded at CS64 must have come from the steep stream banks between the CS44 and CS64, and the 8-month-long post-earthquake low flow rate at CS64, even with the above-mentioned flow increase from upstream, shows that this section of streambed was leaking water to crust below (Figure 11d).

Figure 9 shows the location of all monitoring wells (triangle). Most of them were in the footwall plain areas on the west side of the seismogenic Chelungpu thrust fault, and showed only coseismic water-level changes, whether up or down, but not pre-earthquake changes (Chia et al. 2001, 2008; Wang et al. 2001).

The only exception is SJ well, where the water-level precursor was recorded. It is the only well located near the tip of the hanging wall of the Chelungpu fault (Blue Square, Figure 10), being only 1.5 km away from the surface trace of the fault and 1 km above the fault plane. As shown in Fig. 12, the water level showed an unusual rise 2 days before the earthquake, followed by a 4-cm drop 3 hours before the earthquake.

(B) Understanding the observed stream-flow and water-level changes

To explain this anomalous stream-flow change, King and Chia (2018) proposed a scenario, which is described in more detail as follows: Before the earthquake when the thrust fault got stuck at the hypocenter and the tectonic stress reached the critical level, the hanging wall of the fault gradually bulged and macroscopic tensile fractures began to open up in the ground, first at the surface at higher elevations and then proceeded to lower elevation and greater depth. This process was most prominent in the pre-existing fault zones, including the Shueilikun fault which crosses the monitored stream just upstream of CS64 (Fig. 10). The newly opened fractures allowed a large amount of groundwater (stored shortly after a rainy season) in the steep banks of the stream to flow down to the stream and caused the observed large flow increase 4 days before the earthquake (Fig.11a). The downward-flowing water in the crust together with the critically high shear stress then triggered some slow-slip events to occur from the surface downward along the Shueilikun and other secondary faults (Figure 13b). Propagating at a speed of about 10 km/day (King, 2019), some of these events then triggered a slow-slip event propagating updip along the seismogenic fault plane (Fig. 13b) to cause the water-level anomaly and the earthquake, all within 4 days (Figure 12). The strong seismic shaking together with the large coseismic and post-earthquake fault movements (2.4-10.1 m at the surface trace) then opened up the Shueilikun streambed further, and caused the unusually low post-earthquake flow rate for 8 months (Fig. 11).

Discussion and Conclusions

In fracture mechanics, it has been known for a long time that the tensile strengths of brittle solids are several order-of-magnitude lower than the theoretical values because of stress concentration at the tips of many microscopic flaws (so-called Griffith cracks) in them. Tensile failure usually starts from the worst of these cracks, usually on the surface of the test samples. The same is true for the earth's heterogeneous crust, which not only contains micro-cracks, but also macroscopic faults and defects, where crustal stress are amplified. These are also places where most crustal fluids exist and move to cause hydro-geochemical changes at fixed points of measurement. Thus they are where hydrological and geochemical parameters should be monitored. Yet the currently-used theoretical models usually assume the crust to be isotropic, homogeneous and elastic or poro-elastic.   As a result, some features of hydro-geochemical observations, such as those shown in this study, are left explained, and their reality doubted.

But as this study and other recent studies show, earthquake precursors do exist and they should be earnestly investigated in a renewed effort of earthquake prediction. In such an effort, it is important to develop some realistic crustal models and to find "sensitive sites" to deploy appropriate instruments for long-term continuous monitoring. Such sites are usually located along faults and structurally weakened zones, where the crustal stress is amplified and fluids of various chemical compositions are abundant and free to move. It is such fluid movement that produces the various hydro-geochemical changes recorded at instruments fixed in position. Also, since measurements on the earth's surface are usually made at discrete points and may not represent an overall view, it is important to supplement them with satellite measurements. From the time, location, and spatial/temporal extent of the scientifically detected anomalies, we may then try to predict the time, location, and magnitudes of the forthcoming earthquakes.

Acknowledgements

I would like to thank my former colleagues at the University of Tokyo and National Taiwan University for providing the data used in previous and this studies.

References

Chen, C. C., Huang, C. T., Cherng, R. H., & Jeng, V. (2000). Preliminary investigation of damage to near fault buildings of the 1999 Chi-Chi earthquake. Earthquake Engineering and Engineering Seismology, 2(1), 79-92.

Chia, Y., Wang, Y. S., Chiu, J. J., & Liu, C. W. (2001). Changes of groundwater level due to the 1999 Chi-Chi earthquake in the Choshui River alluvial fan in Taiwan. Bulletin of the Seismological Society of America, 91(5), 1062-1068.

Chia, Y., Chiu, J. J., Chiang, Y. H., Lee, T. P., Wu, Y. M., & Horng, M. J. (2008). Implications of coseismic groundwater level changes observed at multiple-well monitoring stations. Geophysical Journal International, 172(1), 293-301.

Dong, J. J., Wang, C. D., Lee, C. T., Liao, J. J., & Pan, Y. W. (2004). The influence of surface ruptures on building damage in the 1999 Chi-Chi earthquake: a case study in Fengyuan City. Engineering Geology, 71(1-2), 157-179.

Hill, D. P., Reasenberg, P. A., Michael, A., Arabaz, W. J., Beroza, G., Brumbaugh, D., ... & Ellsworth, W. L. (1993). Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. Science, 260(5114), 1617-1623.

Ishida, M. (1992). Geometry and relative motion of the Philippine Sea plate and Pacific plate beneath the Kanto-Tokai district, Japan. Journal of Geophysical Research: Solid Earth, 97(B1), 489-513.

Kato, A., Obara, K., Igarashi, T., Tsuruoka, H., Nakagawa, S., Hirata, N. (2012). Propagation of Slow Slip Leading Up to the 2011 Mw 9.0 Tohoku-Oki Earthquake. Science, 335, Issue 6069, 705-708. DOI: 10.1126/science.1215141

King, C. Y. (1986). Gas Geochemistry applied to earthquake prediction. J. Geophys. Res., 91, 12269-12281.

King, C. Y. (2018). Characteristics of a sensitive well showing pre-earthquake water-level changes. Pure and Applied Geophysics, 175(7), 2411-2424.

King, C. Y. (2019). Kinematics of Slow-Slip Events. In Earthquakes-Impact, Community Vulnerability and Resilience. IntechOpen.

King, C. Y., Basler, D., Presser, T. S., Evans, W. C., White, L. D., & Minissale, A. (1994). In search of earthquake-related hydrologic and chemical changes along Hayward fault. Applied Geochemistry, 9(1), 83-91.

King, C. Y., Azuma, S., Ohno, M., Asai, Y., He, P., Kitagawa, Y., ... & Wakita, H. (2000). In search of earthquake precursors in the water-level data of 16 closely clustered wells at Tono, Japan. Geophysical Journal International, 143(2), 469-477.

King, C. Y., & Chia, Y. (2018). Anomalous Streamflow and Groundwater-Level Changes before the 1999 M7. 6 Chi–Chi Earthquake in Taiwan: Possible Mechanisms. Pure and Applied Geophysics, 175(7), 2435-2444.

King, C. Y., & Manga, M. (2018). Hydrological, Geochemical and Geophysical Changes Related to Earthquakes and Slow-Slip Events: Introduction. Pure and Applied Geophysics, 175(7), 2407-2409.

Kitagawa, Y., Koizumi, N., & Tsukuda, T. (1996). Comparison of postseismic groundwater temperature changes with earthquake-induced volumetric strain release: Yudani hot spring, Japan. Geophysical research letters, 23(22), 3147-3150.

Kobayashi, A. (2014). A long-term slow slip event from 1996 to 1997 in the Kii Channel, Japan. Earth, Planets and Space, 66(1), 1-7.

Koide, K., Tamame, M., & Kobayashi, K. (1997). Heterogeneity of hydraulic conductivity of a fault in ssedimentary sequences at the Tono Mine, central Japan. Rep. PNC TN7410 97-035, pp.30-39, Power Reactor and Nucl. Fuel Dev. Corp., Tono Geosci. Cent., Toki-shi, Gifu-ken, Japan.

Liu, C. Y., Chia, Y., Chuang, P. Y., Wang, C. Y., Ge, S., & Teng, M. H. (2018). Streamflow Changes in the Vicinity of Seismogenic Fault after the 1999 Chi–Chi Earthquake. Pure and Applied Geophysics, 175(7), 2425-2434.

Ouzounov, D., Pulinets, S., Hattori, K., & Taylor, P. (2018). Pre-earthquake processes: A multidisciplinary approach to earthquake prediction studies (Vol. 234). John Wiley & Sons.

Rojstaczer, S., & Wolf, S. (1992). Permeability changes associated with large earthquakes: An example from Loma Prieta, California. Geology, 20(3), 211-214.

Silver, P. G., & Valette-Silver, N. J. (1992). Detection of hydrothermal precursors to large northern California earthquakes. Science, 257(5075), 1363-1368.

Sugihara, K, Hirota, M., & Shiraishi (1991). A hydrogeological modeling process for sedimentary rocks. In Proceedings of the 7th International Congress of Rock Mechanics, ed. Wittke, W., pp. 413-420. A. A. Balkema, Brookfield, Vt., Aachen.

Wakita, H. (1996). Geochemical challenge to earthquake prediction. Proceedings of the National Academy of Sciences, 93(9), 3781-3786.

Wang, C. Y., Cheng, L. H., Chin, C. V., & Yu, S. B. (2001). Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake, Taiwan. Geology, 29(9), 831-834.

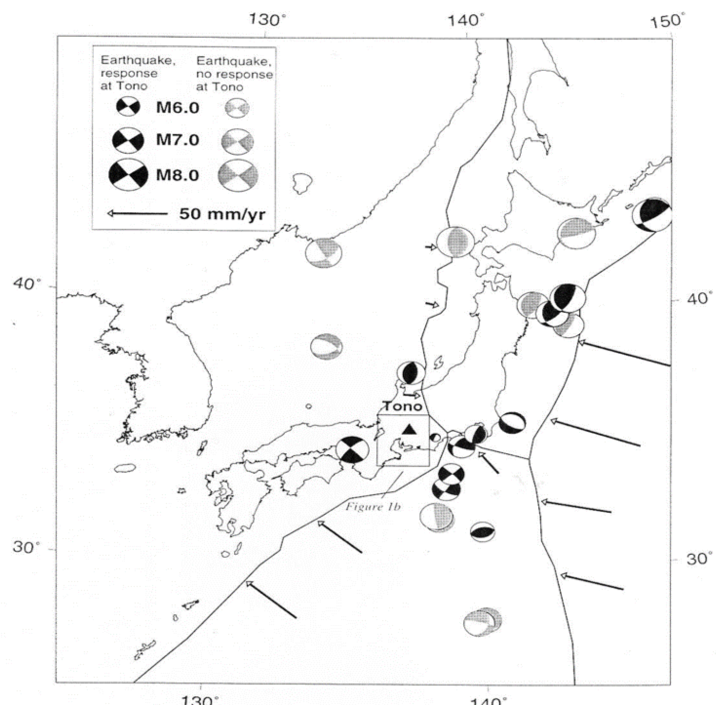

Fig. 1. Tectonic settings in and around Japan, the locations of Tono mine (triangle) in central Japan and larger earthquakes discussed in the paper (beach balls, darker ones showed earthquake-related changes). In central Japan, the Philippine Sea plate in the south is subducting beneath the Eurasian plate to the northwest and is underlain by the Pacific plate from the east (Ishida, 1992), while in

northeastern Japan the Pacific plate in the east is subducting beneath the North American plate to the west. The rectangular local area of Tono is enlarged in Fig. 2. (After King, et al., 1999)

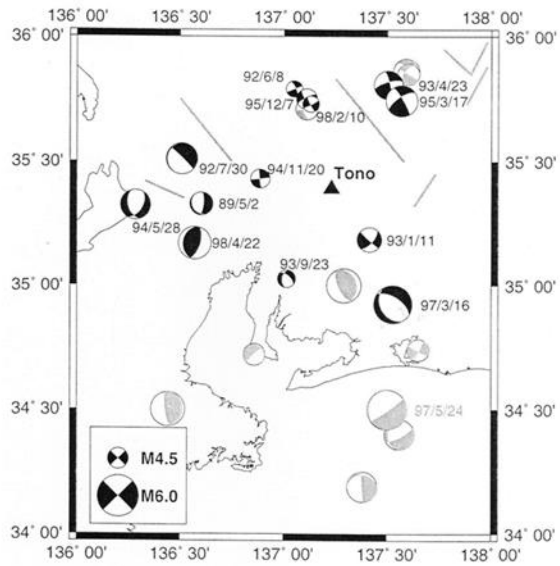

Fig. 2. Locations of Tono mine (triangle) and local earthquakes (beach balls, darker ones showed earthquake-related changes) and active faults (shaded lines). (After King, et al., 1999)

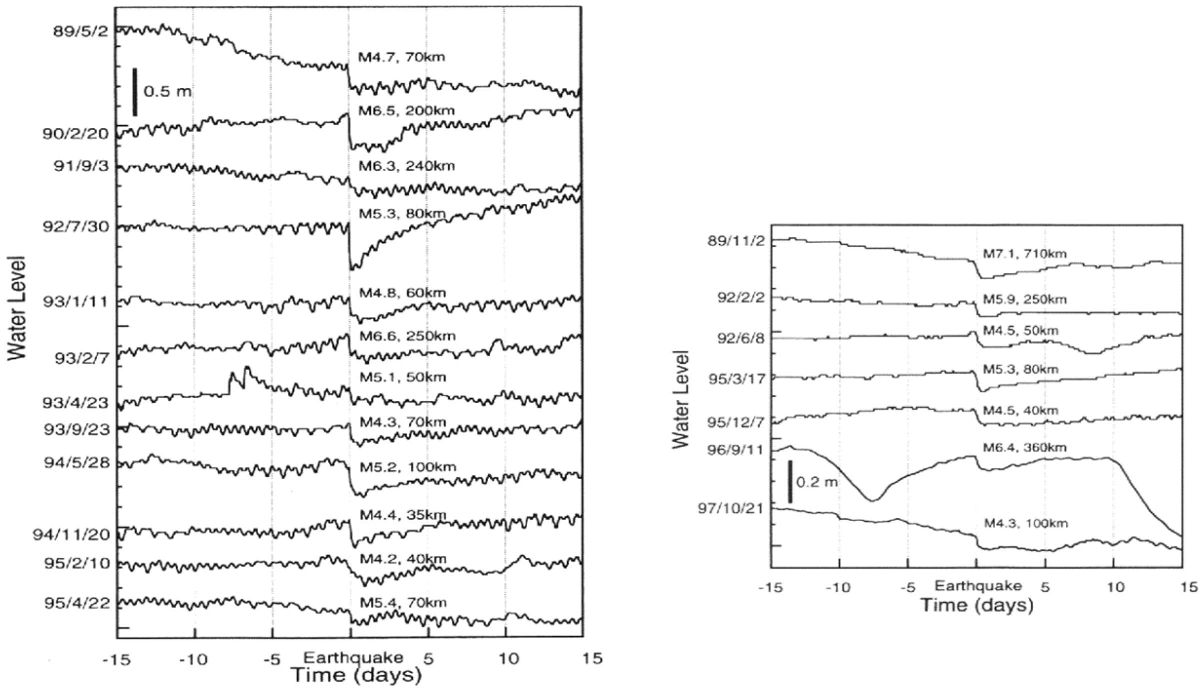

Fig. 3. Left panel shows larger coseismic water-level changes recorded at the sensitive well (SN3), together with earthquake dates, magnitudes, and epicentral distances. Right panel shows smaller coseismic changes after correction of barometric-pressure and tidal effects. (After King, et al., 1999)

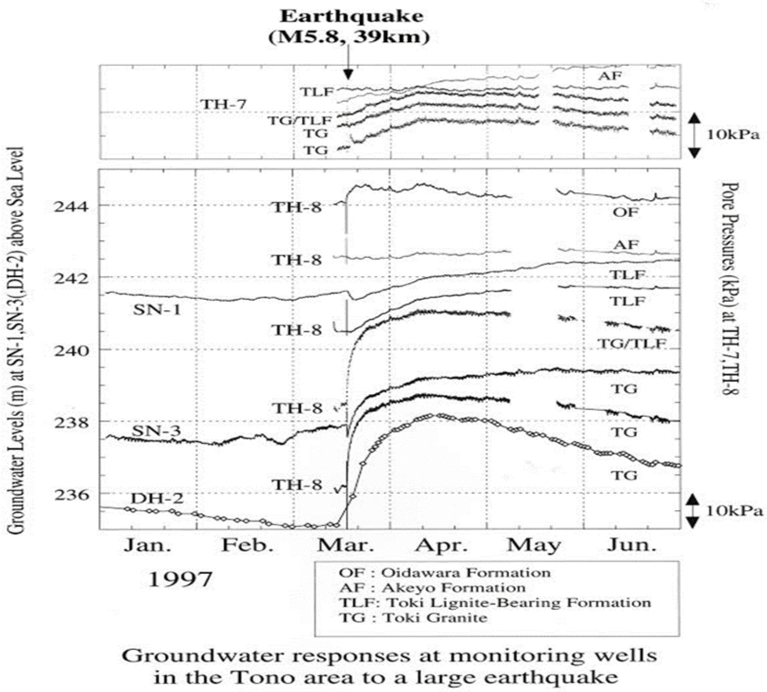

Fig. 4. Coseismic water-level changes at SN1, SN3, TH-7 and TH-8 wells for the magnitude 5.8 local earthquake (at time indicated by the arrow) about 50 km away at a depth of 39 km. (After King 2018)

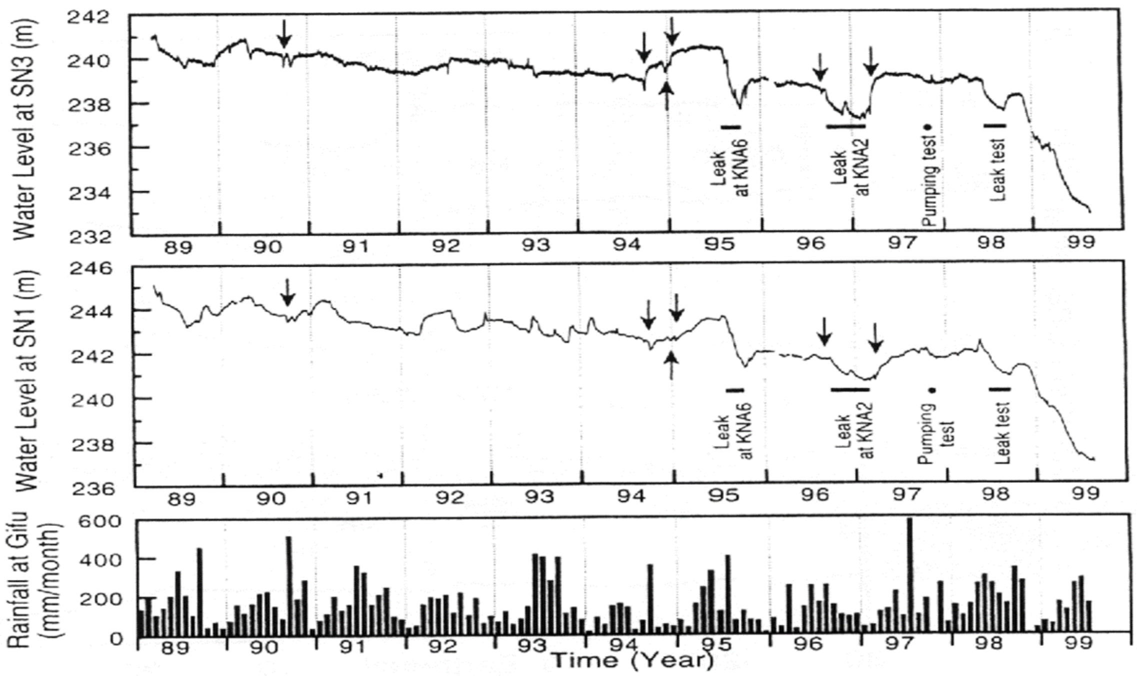

Fig. 5. Long-term water-level data recorded at SN1 and SN3 wells during 1989-99, together with monthly rainfall data. Arrows indicate occurrence of larger earthquakes that showed pre-earthquake water-level changes at SN3. (After King, et al., 2000)

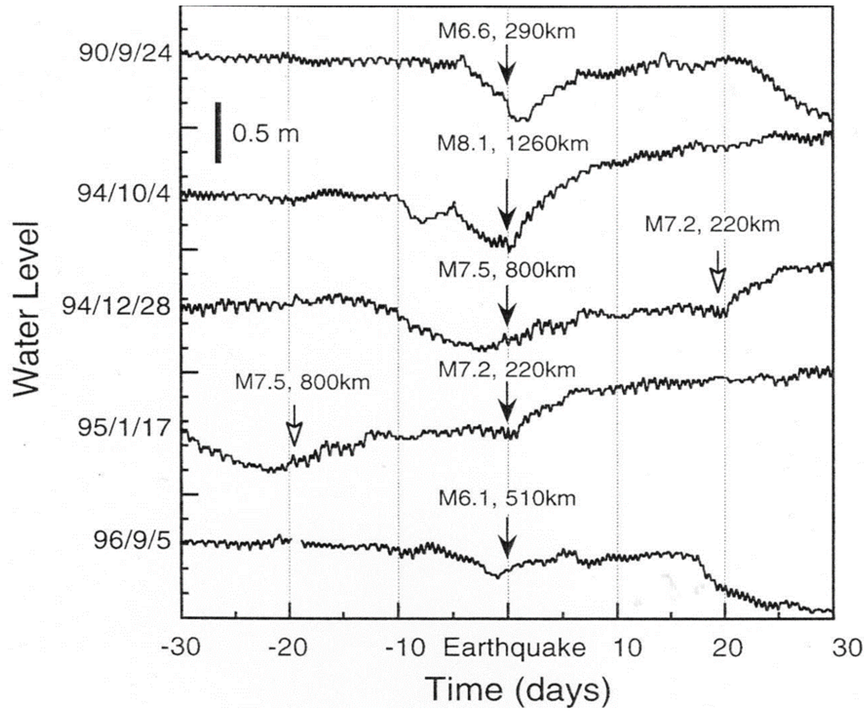

Fig. 6. Pre-earthquake water-level changes recorded t SN3 well for 5 large distant earthquakes (arrows) aligned in the middle of a 60-day time window. Earthquake dates are shown on the left side. (After King, et al. 1999)

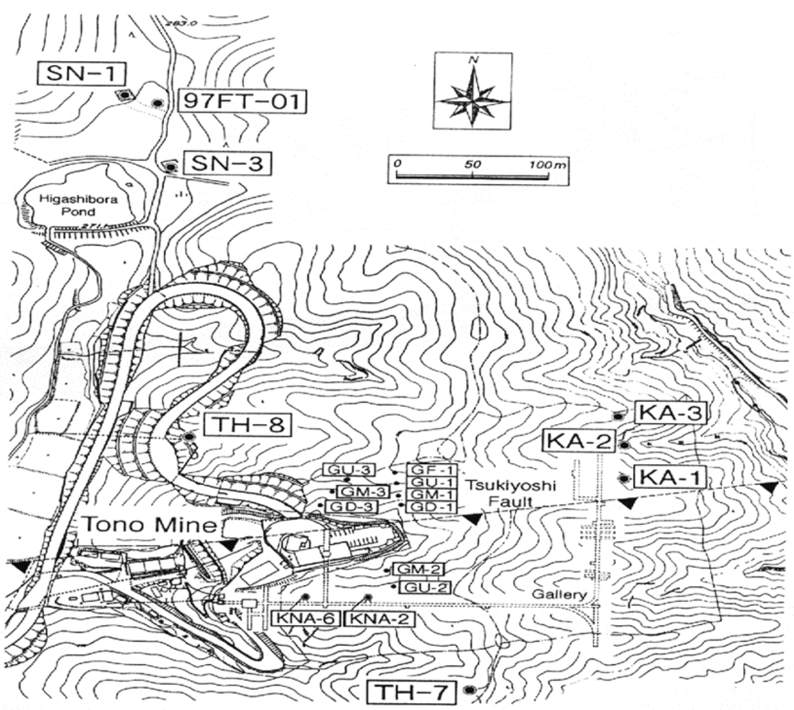

Fig. 7. Map of Tono mine area, showing locations of SN1, SN3, TH-7, TH-8, and other wells (circles). The Tsukiyoshi fault (dashed line), underground gallery (dotted lines), the KNA-1 and KNA2 holes, the topographic contour lines, and roads and various buildings. (After King et al. 1999)

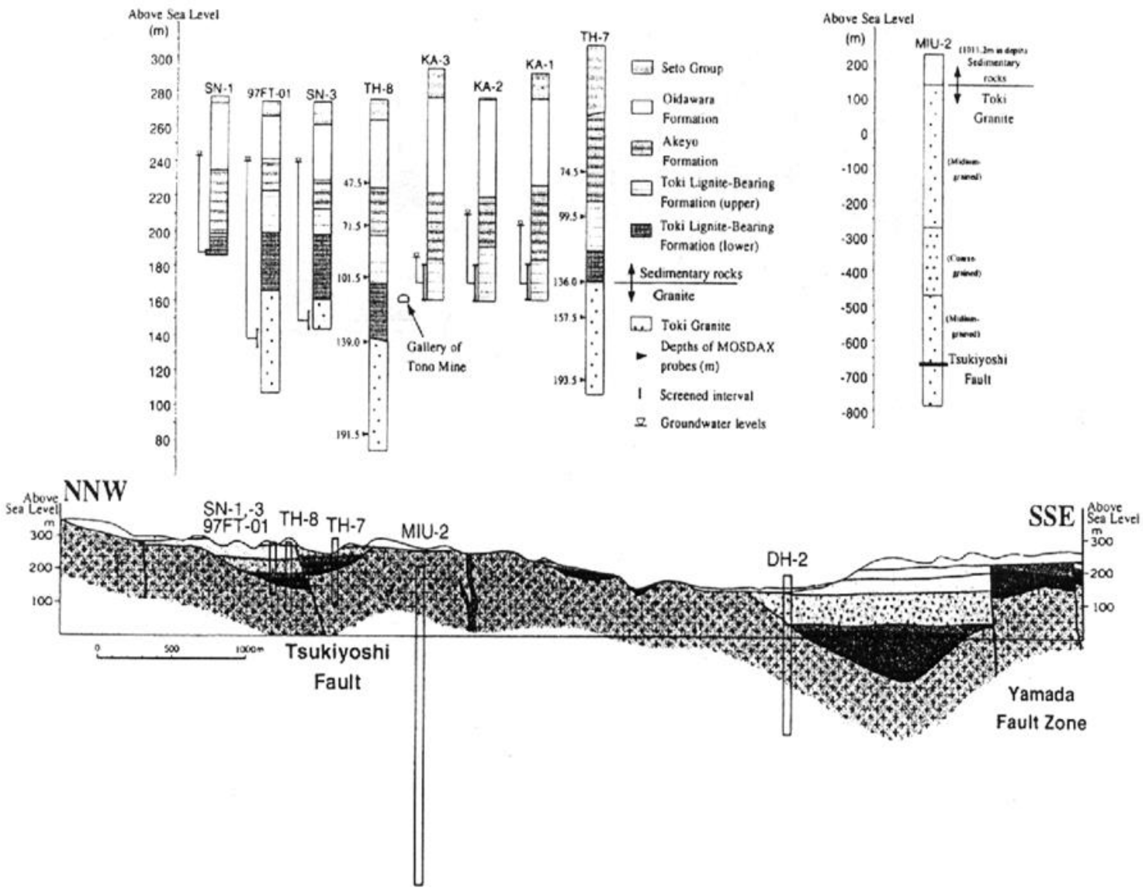

Fig. 8. Geological columns of 8 deeper monitoring wells at Tono (upper panel) and a cross-sectional sketch of the local crust (lower panel). Both SN-3 and Th-8 wells tapped a highly permeable layer (the top 30-40 m of the weathered surface layer of the Cretaceous bedrock, Toki granite, on the same side of the Tsukiyoshi fault. (After King, et al., 2000)

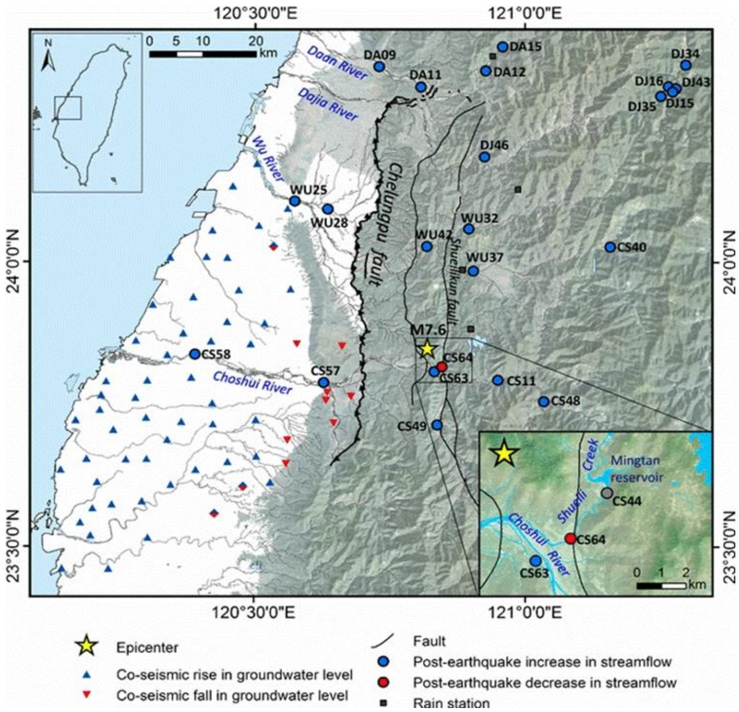

Fig. 9. Location of the 1999 magnitude 7.6 Chi-Chi earthquake (star), water-level monitoring stations (triangles), and stream-flow monitoring stations (circles) in central Taiwan. The upper-left inset shows the location of this area in Taiwan. The lower-right inset shows the location of stream-flow gauges CS64, CS44, and CS63 together with the earthquake epicenter. (After, Liu, et al. 2018)

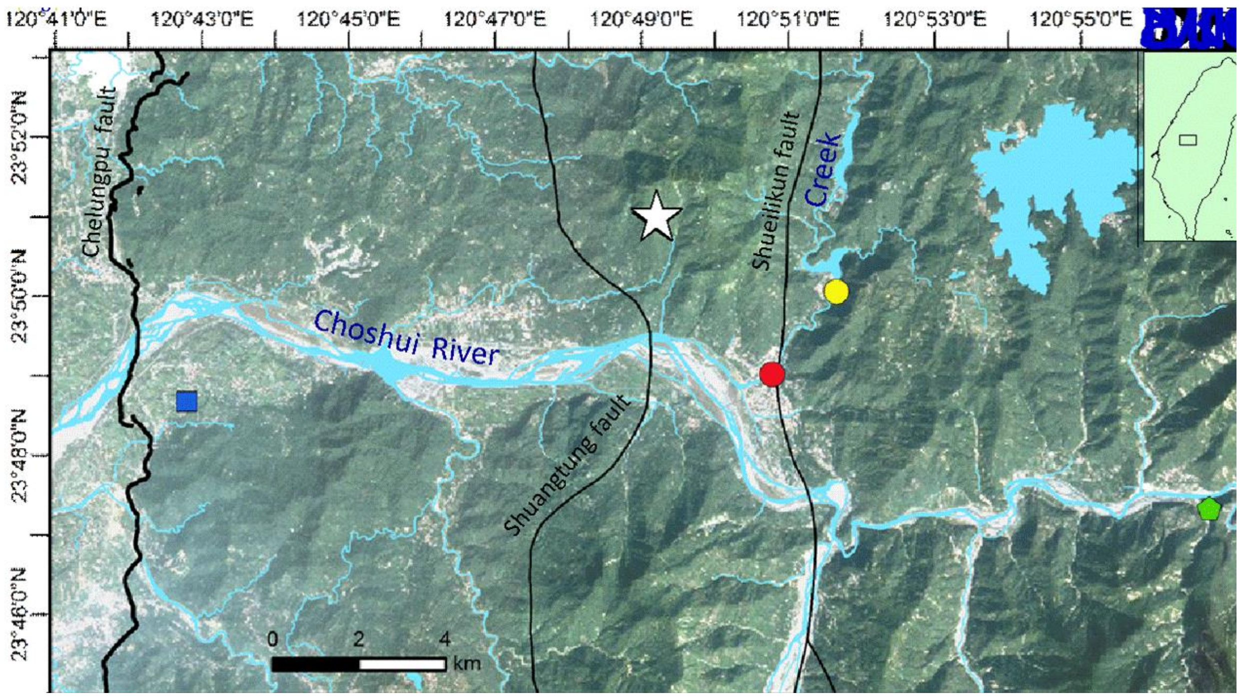

Figure 10. Location of water-level monitoring well SL (blue square) and stream gauges CS64 (red circle) and CS44 (yellow circle) along with the Shueili Creek, Choshui River, Mingtan reservoir and the epicenter of Chi-Chi earthquake (white star) in central Taiwan. The pre-earthquake streamflow and water-level changes were observed at CS64 and SL, respectively. (After King and Chia 2018)

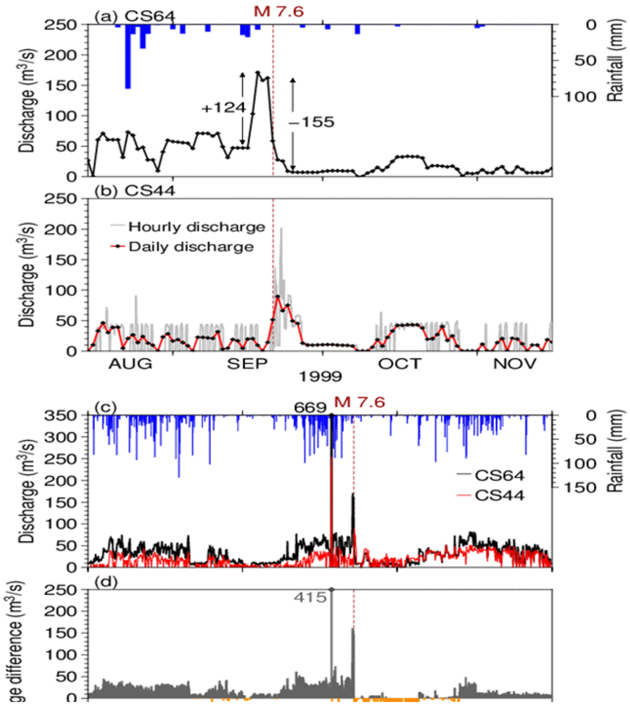

Fig. 11. Stream discharges recorded at gauges on the Shueili Creek near the earthquake epicenter (a) Daily discharges at CS64 from August to November 1999; (b) Daily and hourly discharges at CS44 from August to November 1999; (c) Comparison of daily discharges at CS64 (black line) and CS44 (red line) from 1998 to 2000; (d) Difference in daily discharges between CS64 and CS44. Earthquake time is indicated by the vertical dash line. (After King and Chia 2018)

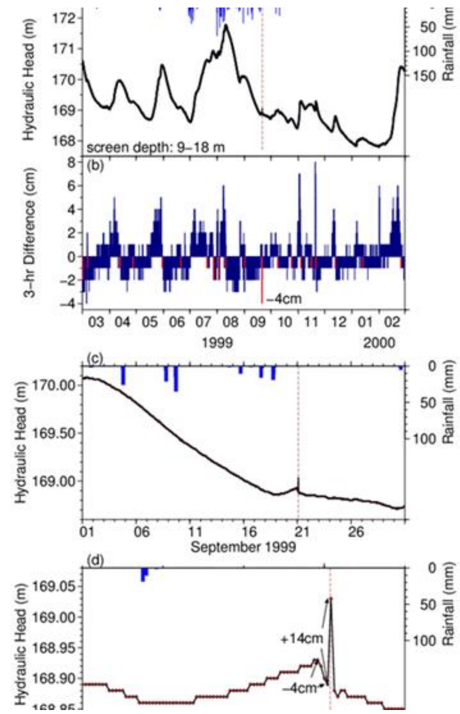

Fig. 12. Groundwater levels recorded at the near-epicenter well SL. (a) Hourly data at SL from March 1999 to February 2000 showing the variation of groundwater level (raw data are listed in ESM 3) and rainfall. (b) The 3-hr difference showing the anomalous of the 4-cm drop before the earthquake. (c) Groundwater level at SL in September 1999 showing an anomalous increase two days before the earthquake. (d) Anomalous groundwater level drop of 4 cm that began 3 hours before the earthquake. The following peak is part of seismic oscillation. (After King and Chia, 2018)

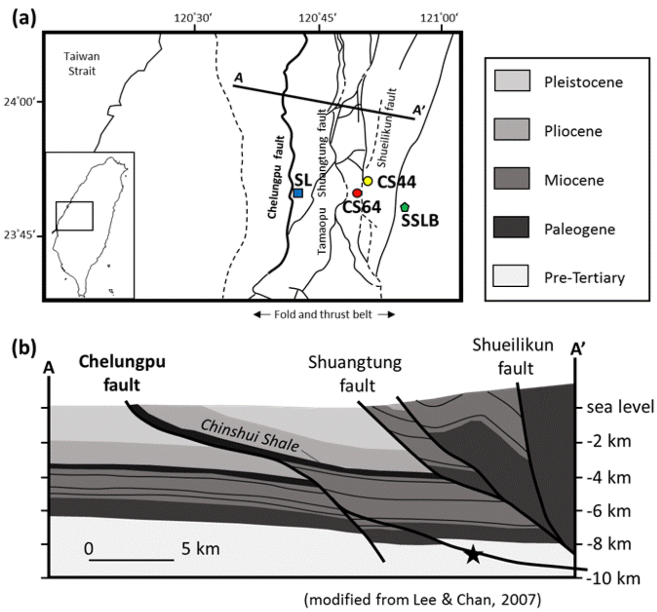

Figure 13. Geological structure of central Taiwan. (a) Planar view of geological structure near Chelungpu fault and the locations of SL, CS64, CS44 and SSLB. (b) Interpreted geological cross-section of A-A′ showing the structure of Chelungpu fault area (Lee and Chan, 2007). The hypocenter of Chi-Chi earthquake is indicated by a star. (After King and Chia, 2018)