

How precise is continuous observation of stress-strain in deep borehole? Examination by invariants of elastic theory.

ISHII, Hiroshi^{1*}, ASAI, Yasuhiro¹, KAWASAKI, Ichiro¹

¹Tono Research Institute of Earthquake Science

Though seismic precursors surely exist, it is considered that they are very small in comparison with coseismic signal caused by the earthquake. However, observations are mostly performed on the surface of the earth where precursory signals are disturbed by the artificial noise and so on, and may not be able to be detected. One possibility to solve these problems is to make observations in deep underground of bedrock where earthquakes occur.

Being based on this idea we have developed multi-component borehole instrument including multi-component strain meters and stress meters with high sensitivity, tilt meters, seismometers, accelerometers, a thermometer and magnetometers for earthquake prediction study. The sizes of the instrument are about 10 cm of diameter and about 8 m of length depending on purposes and combinations of sensors.

Multi-component borehole instruments have been installed in some boreholes of our observation area. The deepest borehole is 1030m deep. Data obtained by the instruments are sent to our institution by online. Our strain meters and stress meters have recorded well strain and stress variations.

In this presentation we report how precise our instruments record stress and strain variations. Our instruments recorded strain and stress seismograms caused by 2011 Tohoku earthquake. By analyzing the records we derived elastic invariants of elastic theory. The invariants derived by several components coincides very well for both one station and different stations. We present the obtained results and discuss goodness of our observation.

Keywords: deep borehole observation, continuous observation of stress and strain, invariants of elastic theory, observation accuracy, stress seismogram of 3.11 earthquake, multi-component borehole instrument

Results of continuous crustal strain observation in vicinity of Mozumi-sukenobe fault

ASAI, Yasuhiro^{1*}, ISHII, Hiroshi¹

¹Tono Research Institute of Earthquake Science, ADEP

The Active Fault Research Group of the Earthquake Frontier Project (Ando, 2007) excavated a 480 m long tunnel across the Mozumi-sukenobe fault. Two major fault zones appeared across the tunnel (e.g. Tanaka et al, 2007). Two strain meters were installed on both sides of the fault zone (Ishii et al, 2007).

The observation as a Earthquake Frontier Project were ended in 2000. Tono Research Institute of Earthquake Science, ADEP has carried out continuous observation of strain since July 2006.

We will present the results of continuous strain observation.

Keywords: Ishii-type borehole strainmeter, in-situ stress measurements, continuous strain observation, Mozumi-Sukenobe fault, Observation in vicinity of active fault

A strain behavior before and after the 2009 Suruga-Bay earthquake (M6.5)

TAKANAMI, Tetsuo^{1*}, Naoshi Hirata¹, Genshiro Kitagawa², Osamu Kamigaichi³, Alan T Linde⁴, Selwyn I Sacks⁴

¹ERI University of Tokyo, ²Research Organization of Information and Systems, ³Japan Meteorological Agency, ⁴DTM Carnegie Institution of Washington

On 11 August 2009 the intraslab earthquake (M6.5) struck the Tokai area. The largest seismic intensity observed was VI- in JMA scale, and it was a felt earthquake in a wide area including the Kanto and Koshin'estu Regions. Tsunamis were observed at and around the Suruga Bay. In the Tokai area, the Japan Meteorological Agency (JMA) continuously monitors strain data by the real time automated processing in the Tokai network. According to JMA, it is unconnected to the anticipated Tokai Earthquake (M8) judging from the acceptable reasons. For instance, it is an intraslab earthquake in the Philippine Sea plate, while the anticipated earthquake is a plate boundary earthquake on the upper side of the Philippine Sea plate. We consider it as an appropriate earthquake for validation of the Tokai network, though the feature of earthquake is different from one of the anticipated earthquake. We here tried to investigate the strain behavior before and after the 2009 Suruga Bay earthquake occurred in the fault zone of the anticipated Tokai earthquake. In actual, the Tokai network of strainmeters has been monitoring the short-term slow slip events (SSE) synchronized with nearby low frequency earthquakes or tremors since 2005 (Kobayashi et al., 2006). However, the earth's surface is always under the continuous influence of a variety of natural forces such as earthquakes, wave, wind, tide, air pressure, precipitation and a variety of human induced sources, which create noise when monitoring geodetic strain. Eliminating these noise inputs from the raw strain data requires proper statistical modeling, for automatic processing of geodetic strain data. It is desirable to apply the state space method to noisy Tokai strain data in order to detect precursors of the anticipated Tokai earthquake. The method is based on the general state space method, recursive filtering and smoothing algorithms (Kitagawa and Matsumoto, 1996). The first attempt to apply this method to actual strain data was made using data from the 2003 Tokachi-oki earthquake (M8.0) recorded by the Sacks-Evertson strainmeter, which has been operating since 1982 at Urakawa Seismological Observatory (KMU) of Hokkaido University in the southern part of the Hidaka Mountains (Takanami et al., 2009). KMU is far 105 km NW of the epicenter of the 2003 Tokachi-oki earthquake. After the earthquake, the data showed a clear episode of contraction for 4 days followed by expansion for 23 days. These signals correlate with increased aftershock seismicity for events greater than M4. The strain changes, together with surface displacements detected by the GPS network, are indicative of propagation of slow slip at depth (e.g. Geographical Survey Institute, 2004). We here review the computational approach to state space method and the results of its application to the strain data from the 2009 earthquakes (M6.5) occurred off Sagami in the Tokai area. Interestingly, for the 2011 Tohoku Earthquake off the Pacific coast no pre-slip was detected by land-based observations even though its magnitude was M9. In order to detect the nucleation of such an earthquake occurring far offshore, high-precision strain data is necessary but was not available.

Keywords: 2009 Suruga-Bay earthquake(M6.5), Strain, Anticipated Tokai earthquake, State-space model

Vertical Crustal Movements in the vicinity of Hanaori fault nearby the campus of Kyoto University(Subsequent Report)

OTSUKA, Shigeaki^{1*}, KATO, Mamoru², KANEKO, Katsuya², ISHIKAWA, Naoto², Satoshi SAKAI²

¹Faculty of Humanities and Sciences, Kobe Gakuin University, ²Graduate School of Human and Environmental Studies, Kyoto University

Precise leveling (spirit leveling) has been carried out in and around the campus of Kyoto University as a part of a basic practical course on earth sciences in Kyoto University. Hanaori Fault, one of the active faults in the Kinki region, runs along the east edge of the campus and the west foot of the Yoshidayama hill. To lead students to an interest in earth sciences including geodesy, monitoring the vertical crustal movements across the active fault by precise leveling was adopted as a subject of the course.

Although some cases resulted in failure, the precise measurements on the accuracy of the first order leveling have been carried out annually for 30 years since 1982. Therefore the changes of height difference in millimeter can be detected.

In this report, the results of the precise leveling along the bench mark net crossing the Hanaori Fault will be shown. The bench mark located halfway up the Yoshidayama hill was rising relative to the ground of the campus of Kyoto University at the rate of 0.001 cm/year before 2000. The rising rate has changed between 2000 and 2004; the bench mark at Yoshidayama has been rising at the rate of 0.05 cm/year since 2000. For the moment, it is not clear what has caused this change of the rising rate of Yoshidayama.

Whether the crustal movements at Yoshidayama were affected by the big earthquake "The 2011 off the Pacific coast of Tohoku Earthquake (M9.0)" or not was of interest. As a result, no effect of the earthquake on the Hanaori Fault was detected by the measurements in 2011. The bench mark at Yoshidayama is rising at the same rate before the earthquake.

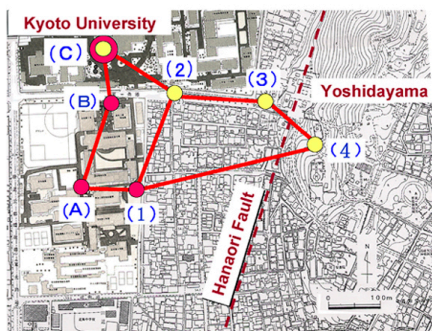


Fig. 1 Leveling net in and around the campus of Kyoto University and Yoshidayama.

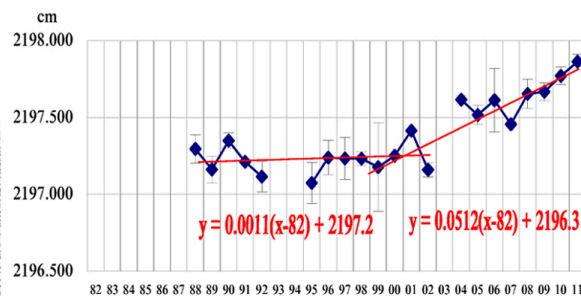


Fig. 2 Height difference change between the bench marks (1) and (4).

3D Analysis of crustal motions of Japan

HARADA, Yasushi^{1*}, KATO, Tadayoshi¹

¹School of Marine Science and Technology, Tokai University

The GPS observation made it much easier to understand the crustal motions. The Geographical Survey Institute of Japan(GSI) has about 1400 GPS stations(GEONET) over Japan for observing Japanese crustal deformations, and the GEONET enabled us to understand how Japan continuously deforming. However, time series plotting or vector arrow figures of the GPS data are sometimes not easy to understand the three dimensional deformation with time.

In this study, we created 3D animations for Japanese crustal deformation using GPS data obtained by GSI, and make it easier to understand the Japanese crustal motions. The GSI already had created animation of Japan for horizontal motion of only limited time and area, whereas we can make animations for three dimensional deformation of any given time and area if the GPS data are available. The newly created animations revealed the detailed crustal deformation in Japan.

We compared our results to a 100 years leveling data of Japan and the geological data for about two million years. In spite of time differences, a lot of similarities can be seen on the pattern of deformation of Japan, and amount of crustal motions were comparable between GPS data and leveling data.

Keywords: GPS, crustal deformation, 3D Analysis

Spatial variations in Fault Coupling on the northern portion of the Great Sumatran Fault

ITO, Takeo^{1*}, ENDRA, Gunawan¹, KIMATA, Fumiaki¹, TABELI, Takao², OHTA, Yusaku³, MEILANO, Irwan⁴, Agstan⁵, Irwandi Nurdin⁶

¹Nagoya University, ²Faculty of Science, Kochi University, ³Tohoku University, ⁴ITB, ⁵BPPT, ⁶Syah Kala University

The Great Sumatran Fault system in Indonesia is a major right-lateral strike-slip trench-parallel system that can be divided into several segments, most of which have ruptured within the last century. This study focuses on the northern portion of the fault system which contains a 200-km-long segment that has not experienced a major earthquake in at least 170 years. In 2005, we established the Aceh GPS Network for the Sumatran Fault System (AGNeSS) across this segment. AGNeSS observes large displacements which include significant postseismic deformation from recent large megathrust earthquakes as well as interseismic deformation due to continued elastic loading of both the megathrust and the strike slip system. We parameterize the displacements due to afterslip using a model based on a rate- and state-dependent friction formalism. Using this approach, we are able to separate post-seismic and inter-seismic contributions. From the interseismic component, we infer the depth of shallow aseismic creep and deeper locked segments for the Great Sumatran Fault. In the northern portion of this fault segment, we infer aseismic creep down to 7.3 \pm 4.8 km depth at a rate of 2.0 \pm 0.6 cm/year. In the southwestern portion of the segment, we estimate a locking depth of 14.8 \pm 3.4 km with a downdip slip rate of 1.6 \pm 0.6 cm/year. This portion of the fault is capable of producing a magnitude 7.0 earthquake.

Keywords: Sumatran fault, fault coupling, Monte Carlo method

Surface motions prior to mega earthquakes by using GPS data

TSURUTA, Natsumi^{1*}, HATTORI, Katsumi¹, HAN, Peng¹

¹Graduate School of Science, Chiba University

Measurements of surface deformation can be used to understand complex stress changes underground. Stress gradually accumulates on strata until it exceeds thresholds that strata can withstand, at which point abrupt tectonic motions occur, causing earthquakes, rupture and intense vibration. The elastic deformation caused by force accumulation in strata during seismogenic processes may also be observable. In this study, we try to find out any unusual behaviors of surface motion prior to mega earthquakes by using GPS data provided by The Geospatial Information Authority of Japan (GSI).

First, we have investigated short-term deformations prior to the 2003 M8.0 Hokkaido earthquake and the 2011 M9.0 Tohoku earthquake. GPS data near the epicenters has been checked. It is found that one day before the M8.0 Hokkaido earthquake, some pre-slip may have occurred at the stations near the epicenter. As for the M9.0 mega event, two days before there have been significant deformation in the region close to the focal area. However, because of the M7.3 foreshock two days before, the deformation results may possible affect by the co-seismic slip and the afterslip.

Then, we have monitored long term motion of GPS stations associated with the M9.0 event. GPS data of three stations on the Pacific coast and three stations on Japan Sea coast in the Tohoku region have been selected to analyze. It is found that about one year before the mega earthquake, the direction of motions of Japan Sea region began to change from east to west. And around 40 days before, the whole Tohoku region began to move to east. The details of the phenomena and possible mechanism will be discussed in our presentation.

Effects to the crustal movements of the Tokai region by 2011 Tohoku Earthquake

NOMURA, Shinichi^{1*}, SATOMURA, Mikio¹, IKUTA, Ryoya¹, SHIMADA, Seiichi², KATO, Teruyuki³, HARADA, Yasushi⁴

¹Department of Geosciences, Shizuoka University, ²NIED, ³ERI, University of Tokyo, ⁴School of Marine Science and Technology, Tokai University

On March 11, 2011, a massive earthquake of Mw9.0 occurred along the plate boundary off the Tohoku region, Eastern Japan. This was the largest earthquake in the recent Japanese history. Its co-seismic and after-seismic crustal deformation affected the crust of all over Japan and also triggered active seismicities.

Tokai region, central Japan, is located at the plate boundary zone between subducting Philippines Sea Plate and Amurian Plate. In this region, Tokai Earthquake has been expected to occur in the near future along the plate boundary. Some of the induced earthquakes of the Tohoku Earthquake occurred in the Tokai region. Therefore, this massive earthquake might change the conditions of the crust in this area. We estimated the effects of the Tohoku Earthquake which was appeared in the crustal deformation in the Tokai region.

Very dense observation network has been expanded in the Tokai region. We obtained GPS station coordinates by analyzing observation data of 84 stations in Shizuoka, Aichi, Nagano and Yamanashi Prefectures. These GPS stations included GEONET (GPS Earth Observation Network System) and JUNCO (Japanese University Consortium for GPS Research). We processed their data during the period of 200 days from February to September 2011. We used GAMIT ver.10.4 software for analyzing observation data. Reference frame was ITRF2008. At first, we estimated co-seismic displacements of each stations from the obtained coordinates. Then, we calculated after-seismic velocity field and dilatation velocities, and compared them with the ones calculated in the previous study (Hashimoto et al., 2011) from GPS observation during the period before the Tohoku Earthquake, August 2005 to December 2006.

Our results showed clear dilatation velocity distribution change before and after the Tohoku Earthquake on March 11, 2011. The effect of the afterslip was quite significant, and also the coupling condition between Philippine Sea plate and Amurian Plate may be changed, although the Tohoku Earthquake was the event which occurred in subducting zone of the different pair of plates from the Tokai region.

Keywords: GPS, crustal movements, Tokai region, Tohoku Earthquake, strain velocity, temporal change

Plate Coupling and Deformation of Forearc Sliver in Southwest Japan

ICHTANI, Shozui^{1*}, TABELI, Takao², TANAKA, Mikito¹

¹Graduate School of Integrated Arts and Sciences, Kochi University, ²Faculty of Science, Kochi University

The Philippine Sea plate has subducted beneath southwest Japan at the Nankai Trough. Oblique subduction of the plate and strong coupling on the plate interface have deformed the overriding plate in two different modes: crustal shortening in the direction of plate convergence and long-term lateral movement of the forearc sliver along the Median Tectonic Line (MTL). In this study, we decompose crustal deformation field into these two modes using three-component GPS displacement rates (velocities) from nationwide continuous GEONET and supplementary campaign networks across the MTL.

Horizontal and vertical velocities are obtained from final coordinate (F3) time series at 333 sites of GEONET from Kinki to Kyushu regions during 2004-2009. The original velocity data contain both of the elastic compressional deformation and lateral forearc movement. At first we correct the original velocity data to remove the latter. We assume that the forearc slides at a constant rate along the MTL but its fault plane is fully locked from surface to a depth of 15 km. Next, using the corrected velocity data, we estimate interseismic slip deficit distribution on the plate interface reproduced by more than 500 triangular elements. Then site velocities calculated from the above plate coupling distribution are compared with the original GEONET and campaign velocities. Residuals between the original and calculated velocities illustrate forearc lateral motion and locking effect of the MTL fault plane. Now we can use the residual velocity field to estimate slip-locking distribution on the MTL fault plane. At last we check the first-assumed constant rate of the forearc block motion by comparing it with the estimated slip deficit rate on the MTL. Since no clear evidence of creep motion has been obtained from the surface observation across the MTL, the two rates should agree with one another. In this analysis the optimal rate of the forearc block motion is 5 mm/yr. In the eastern Shikoku the slip pattern is nearly pure strike-slip at a rate of 2-4 mm/yr. In contrast significant normal component is recognized together with strike-slip component of about 5 mm/yr in the western Shikoku.

In the above modeling we assume a constant block rate of the forearc sliver. To investigate internal deformation of the sliver we calculate strain distribution after removing the effect of the plate convergence. We recognize small E-W compression in the eastern Shikoku but the compression is altered by E-W extension in the western Shikoku and the principal axis of the extension rotates counter-clockwise gradually toward a N-S trending in the central Kyushu. This means that the forearc sliver is not absolutely rigid and its driving force is not only the oblique subduction of the plate. Further detailed modeling is needed to better understand deformation mechanism of the forearc sliver.

Keywords: Philippine Sea plate, the Median Tectonic Line, GPS, Nankai Trough

A new interpretation of the slow slip event in the Tokai region

OCHI, Tadafumi^{1*}, KATO, Teruyuki¹

¹ERI, Univ. Tokyo

In the Tokai region, central Japan, anomalous displacements had been detected by GEONET during the period from mid-2000 to mid-2005 and they seem to have been caused by a slow slip event (SSE) beneath the Lake Hamana and have been called as “Tokai SSE”. Previous studies introduced the Tokai SSE by the inversion of data which is the difference between the observed displacements and the displacements due to the continuous plate coupling. However, this model has no physical meaning. The present study claims that the combined effects of the slow slip events (or forward slip) and the plate coupling (or so-called back slip) should represent the state of the plate interface. In addition, the temporal change of the plate coupling has not been taken into account in the previous studies. In this study, we estimated the state of the plate interface by the geodetic inversion method without the assumption of the steady state coupling in order to estimate the temporal change of the coupling and slip process on the plate interface.

The data used in this study are the GPS data taken from the GEONET and the leveling data published by GSI for the period from July 1996 to June 2009. In order to examine the temporal change, we divided the entire period into 12 epochs. The duration of each epoch is two years and the neighboring two epochs overlap one year. The two-year averaged rate of crustal deformation are derived from the GPS data and the leveling data separately and are taken into the geodetic inversion simultaneously.

The estimated distributions of the strain accumulating and releasing areas, by which “strain accumulating area” indicates a area of slip deficit and accumulates in the continental wedge and vice versa, suggested that the whole period was able to be divided into three sub-periods depending on the emergence of the strain releasing area. The strain releasing area emerged in the period from 2000 to 2005, which is consistent with the duration of the Tokai SSE in the previous studies. The maximum value of the strain releasing was about 20 mm/yr and the depth was around 30-40 km, while the maximum value of the Tokai SSE was about 35-50 mm/yr in the previous studies. Compared with the previous studies, the present study showed that only the deeper portion of the Tokai SSE really released the strain. The total amount of the released strain was equivalent to the seismic moment of $M_w \sim 6.6$, while the Tokai SSE was equivalent to $M_w \sim 7.0$ to 7.1. Therefore the previous studies overestimated the released strain.

The spatial distribution of the interplate coupling also changed temporally, whereas the coupling of the area had been assumed to be time invariant in the previous studies. It had extended along the plate interface to a point beneath the Lake Hamana before the emergence of the strain releasing area, and then became narrower with the emergence of the strain releasing area, and then had not recover the original distribution after the end of strain releasing process. Although the distribution of coupling changed with time, the maximum value of the interplate coupling did not change; 35 mm/yr through the entire period from July 1996 to June 2009. The maximum value estimated in this study were almost the same as the maximum coupling estimated by the previous studies.

The results also revealed that the distribution of the strain releasing area well coincide with the hypocenters of the low frequency events which occurred repeatedly near the plate boundary. The previous studies inferred that the distribution of the Tokai SSE is shallower than that of the strain releasing area in the present study.

Therefore the Tokai slow slip and the low frequency events were thought to be spatially segregated. The results of present study may require a change of the view about the relationship between these two sorts of strain releasing processes, which may be important for the study of background physics.

A rainfall correction of the strainmeter for detecting a small short-term change (2)

KIMURA, Kazuhiro^{1*}, TSUYUKI, Takahiro², SUGANUMA, Issei², FUJITA, Kenichi²

¹Meteorological Research Institute, ²Japan Meteorological Agency

A present rainfall correction of the strainmeter for forecasting of the Tokai earthquake has a problem. The present rainfall correction has a effect that smoothes off a sharp change by the rainfall and holds down the peak of the rainfall noise, but it has a rainfall effect for a long time slowly. It is difficult to detect a small short-term change while such as the rainfall effect. It is desirable for a trend to be constant to detect the small short-term change.

We considered that the reply of the strainmeter by the rainfall is effect of the load by the rainfall. We tried to a rain fall correction of the volume strainmeter, a simple tank model of one level or two levels got a good result than the AR-method. (Kimura et al., 2011) This is because a tank model can express the increase of the outflow coefficient with the increase of the rainfall accumulation.

We retried to a rain fall correction of the strainmeter by the tank model of three levels which is used as Soil Water Index of JMA. We estimated many parameters of the tank model of three levels by the SCE-UA method. We could obtain a better result by using a complicated tank model about some observation station. We explain these results.

Keywords: Strainmeter, Rainfall correction, Tank model, SCE-UA method

The removal of the postseismic crustal deformation from the GPS data

KIMURA, Kazuhiro^{1*}, KOBAYASHI, Akio¹, Hiroshi HASEGAWA²

¹Meteorological Research Institute, ²Japan Meteorological Agency

JMA monitor the GPS data of GSI by spatial Monitoring (Kobayashi, 2007) for forecasting of the Tokai earthquake. This output is published as the JMA report of Earthquake Assessment Committee for Areas under Intensified Measures against Earthquake Disasters. Offset of the maintenance and earthquake and trend is removed from the GPS data. But JMA couldn't monitor the GPS data because of the postseismic crustal deformation which occurred after the 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0). The postseismic crustal deformation may continue for several decades. It is necessary to remove the postseismic crustal deformation from the GPS data to monitor the phenomenon that is going to happen now. Therefore, we tried to estimate the parameters of the postseismic crustal deformation.

We use the combination of a logarithmic function and an exponential function as the postseismic crustal deformation. We estimate some parameters by the SCE-UA method so that the total of the difference at 30 day is minimized. We explain the result that removed the postseismic crustal deformation of the 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) or the Tokachi-oki Earthquake in 2003 (Mw 8.0).

Keywords: GPS, postseismic crustal deformation, SCE-UA method

Short-term Change of Permeability after Tohoku Region Pacific Coast Earthquake Observed at Rokko-Takao Station

MUKAI, Atsushi^{1*}, OTSUKA, Shigeaki²

¹Nara Sangyo University, ²Kobe Gakuin University

The 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011 caused the step-like increase of groundwater discharge by 250ml/s as well as the step-like changes of strain by about 10^{-7} at Rokko-Takao station. The magnitude of the atmospheric pressure admittance of groundwater discharge increased by 80% just after the earthquake compared with before the earthquake. The pressure admittance has been recovering to the original level in about one year after the earthquake. The station is located in the fracture zone of Manpukuji fault. It is considered that the change of the pressure admittance on the earthquake was caused by the increase of permeability due to outflow of plugging components such as mud from the fracture zone. In this study, we estimated the secular change of permeability of the fracture zone nearby the station and investigated the characteristics of re-plugging of the fracture due to accumulation of mud and so on.

Rokko-Takao station is located in the emergency evacuation road for the Shin-Kobe tunnel, and crosses Manpukuji fault with the east-west strike. In the station, three components strainmeter (ST1:N81°W, ST2:N39°E, ST3:N21°W), three extensometers in the direction of N69°E (EX2, EX3, EX4), the groundwater discharge meter and the groundwater level meter were installed. The observation has been performed continuously with the sampling intervals of 0.5 second and 10 minutes. We calculated the tidal strains by applying the tidal analysis program BAYTAP-G (Tamura et al., 1991) to the observed data of strain. Mukai and Otsuka (2008) reported that the tidal amplitudes of strain had been recovering secularly by a few % per year since 1995 Hyogoken Nanbu Earthquake. It was considered that the healing of the fracture zone caused increase of the Young's modulus and reduced the tidal amplitudes.

The ordinary seepage rate of groundwater at the station is about 550ml/s. The groundwater discharge rate increased to 800ml/s just after the earthquake. After the earthquake, the groundwater discharge rate decreased to 300ml/s in a few days and recovered to the original rate in a few months. Strain steps due to the earthquake at the station showed the positive dilatation about 10^{-7} , which was calculated by using the fault model of Geographical Survey Institute. The low discharge of groundwater during a few months after the earthquake might be caused by the decrease of pore pressure due to the extension of the surrounding crust. On the other hand, the rapid increase of groundwater discharge on the earthquake might be caused by the increase of permeability due to the outflow of plugging components such as mud from the fracture zone.

The pressure admittance of the groundwater discharge in 2010 was estimated to be +3.4ml/s/hPa, which was positive in case that decrease of the atmospheric pressure caused the increase of groundwater discharge. This admittance shows that groundwater is drawn from the fracture zone by decrease of the atmospheric pressure. We estimated the variations of the pressure admittance by applying BAYTAP-G to the groundwater discharge observed since March 12, 2011. In this calculation, we obtained the pressure admittances for four terms. Each term was 90 days and was shifted by 67 days from the previous term. The pressure admittance just after the earthquake was estimated to be +6.1ml/s/hPa. We considered that this large pressure admittance was caused by the increase of permeability as mentioned in case of the increase of groundwater discharge on the earthquake. The pressure admittance has been decreasing to +4.0ml/s/hPa at the end of 2011. It is suggested that the plugging of the fracture due to accumulation of mud and so on caused the short-term decrease of permeability. This plugging of the fracture might be beginning to the long-term healing process of the fracture zone shown by analysis of the tidal strain.

Keywords: groundwater discharge, strain, permeability, The 2011 off the Pacific coast of Tohoku Earthquake

In-situ calibration for various multi-component borehole strainmeters

MATSUMOTO, Norio^{1*}

¹GSJ, AIST

Geological Japan, AIST has constructed fourteen observatories in and around expected focal zones of the Nankai and Tonankai earthquakes to monitor groundwater and borehole strain for prediction research of Nankai and Tonankai earthquakes. The Ishii's multi-component borehole strainmeter or the Gladwin Tensor Strain Meter (GTSM) was deployed at each observatory. Moreover, the Ishii's analog multi-component strainmeter or the Sacks-Evertson-Sakata multi-component strainmeter was deployed near some active faults. Here I represent the results of in-situ calibration for the various multi-component borehole strainmeters, and evaluate the results.

The in-situ calibration for the borehole strainmeter, tidal response of the borehole strainmeter and theoretical tide are used which is the same method of Matsumoto et al. (2010). Oceanic tidal loading of the theoretical tide is calculated by green's function at arbitrary depth for a surface point load (Kamigaichi, 1998) and the modified GOTIC2 program which can apply the green's function to the calculation of theoretical strain. The calibration coefficients are evaluated by long-period surface wave data observed by the borehole strainmeter and diagonal and/or non-diagonal elements of the calibration matrix.

All calibration coefficients for the eleven Ishii's strainmeters and one GTSM are reasonable, further calibration is needed for other three GTSMs. The results of in-situ calibration for the Ishii's analog multi-component strainmeters or the Sacks-Evertson-Sakata multi-component strainmeters are also evaluated.

Keywords: strainmeter, in-situ calibration

Vertical crustal deformation in Kii Peninsula from 1972 to 2009 deduced from leveling data

KOBAYASHI, Akio^{1*}

¹Meteorological Research Institute

Leveling data for the period from 1972 to 2009 in Kii Peninsula, Japan, were investigated to characterize unsteady vertical deformation. We estimated the steady vertical deformation rate at each GEONET GPS station by averaging the daily coordinates for the periods from January 1997 to January 2000, and between January 2007 and January 2010, avoiding the period of the large earthquakes.

First-order leveling surveys have been conducted repeatedly every several years since the 1970s. We determined crustal displacements by comparing leveling data from successive surveys. We subtracted subduction-related steady component derived by the GPS from the distribution of vertical crustal displacements during periods between leveling surveys. If any episodic events have not occurred, they should show little spatial variation around zero vertical displacement. However, the residual data clearly show uplift on the southern Kii Peninsula for the period from 1972.0 to 1979.6. The uplift is slightly left for the period from 1979.6 to 1983.5. It suggests that the after slip of the 1944 Tonankai earthquake and/or the 1946 Nankai earthquake remains until the early 1980s. Unsteady vertical deformation is not seen in the period from 1983.5 to 2009.0. At least a long-term slow slip event equivalent to that of Bungo channel or Tokai does not seem to occur in Kii Peninsula since 1972.

Keywords: leveling, vertical crustal movement, Kii Peninsula

In-situ calibration of NIED Hi-net tiltmeter data

KIMURA, Takeshi^{1*}, HIROSE, Hitoshi², MATSUMOTO, Norio³, Osamu Kamigaichi⁴

¹National Research Institute for Earth Science and Disaster Prevention, ²Graduate School of Science, Kobe University, ³National Institute of Advanced Industrial Science and Technology, ⁴Japan Meteorological Agency

At every Hi-net observatory operated by National Research Institute for Earth Science and Disaster Prevention (NIED), a high-sensitivity accelerometer (tiltmeter) is installed in a borehole sensor capsule accompanied by a high-sensitivity velocity seismometer. Horizontal components of the sensor have been used as a tiltmeter and the recorded ground tilt data is useful to monitor crustal activities such as slow slip events in southwest Japan [e.g., Obara et al., 2004]. In this study, we present the results of in-situ calibration of the ground tilt data [Matsumoto et al., 2010].

For the in-situ calibration of the borehole tiltmeters, we compare observed amplitudes and phases of M2 and O1 tidal constituents with theoretical ones. From the observed tilt data, we extracted these tidal amplitudes and phases using the BAYTAP-G software [Tamura et al., 1991]. The parameters of theoretical tidal constituents are estimated by a modified version of the software GOTIC2 [Matsumoto et al, 2001]. In order to compute the precise ocean tidal loading effect on the borehole tiltmeters, we use Green's function applicable to arbitrary depths due to surface point loading [Kamigaichi, 1998] and the GOTIC2 program with this Green's function modified by Kamigaichi.

We calibrated ground tilt data at 31 Hi-net stations in Shikoku. The observed amplitudes and phases of M2 and O1 tidal constituents are obtained by averaging the estimated values for a 90-day time-window incremented at one day. Ratios of the observed amplitudes to the theoretical ones range from 0.7 to 1.5, and are consistent with the results of Matsumoto et al. [2010] where tiltmeters operated by Geological Survey of Japan, AIST, in Kii Peninsula were calibrated. Differences between observed and theoretical phases are smaller than 20 degrees, and we can confirm the validity of azimuths of borehole sensors estimated by Shiomi et al. [2003] based on teleseismic waves. However, the NS component at MISH station shows relatively large differences between observed and theoretical tidal constituents: amplitude ratio is 0.4 and phase difference of M2 constituent is 50 degrees. A possible cause of this discrepancy is that the accuracy of the calculated ocean tidal loading effect on this station is not sufficient because this station is located on the Sadamisaki peninsula, which has very complicated coastlines.

Keywords: ground tilt data, in-situ calibration, Hi-net

Search for Creep Signals along the Sagaing Fault Using ALOS/PALSAR Interferometry

FURUYA, Masato¹, SUN, Shuoshuai^{1*}

¹Department of Natural History and Sciences, Hokkaido University

Sagaing fault is known as a ~1000 km continental transform fault between the India and Sunda plates, and it is one of the great right-lateral strike-slip faults of Southeast Asia. As slip rate is the important aspect of Sagaing fault, during the past 30 years, seismologists did their best to estimate the slip rate in order to get a close value. The value of slip rate estimated from 35.4 mm/yr by Curray et al. (1982) to 18.5 mm/yr suggested by Myint Thein et al. (1998) changes by different seismologists. Since GPS become useful around 21st century, Vigny et al. (2003) used two years GPS observations to estimate 18 mm/yr of elastic deformation across the central Sagaing fault, and Meade (2007) estimated the rate using GPS observations in a block model which suggests that the strike-slip rate between the Indian and Southeast Asian Plate is 17 and 49 mm/yr at across the central and northern Sagaing fault, respectively.

Whereas InSAR is a powerful technique to map the Earth's surface deformation, to our knowledge, no previous studies have been performed along the Sagaing fault, presumably because shorter-wavelength SAR data did not allow preserving interferometric coherence over the densely vegetated regions. The L-band ALOS/PALSAR, however, could keep good coherence even in vegetation, so that we can map out the surface deformation if the fault is deforming with detectable amplitude. As a preliminary study, we applied InSAR technique to such PALSAR data pairs that span 2-3 years if the fault is undergoing creeping signals like found along the San Andreas Fault in the US west coast.

Keywords: creeping signals, right-lateral, strike-slip, slip rate, InSAR

Crustal deformation in and around Beppu-Shimabara Graben by continuous dense GPS Network

NAKAO, Shigeru^{1*}, MATSUSHIMA, Takeshi², OHKURA, Takahiro³

¹GSSE, Kagoshima Univ., ²SEVO, Kyushu Univ., ³AVL, Kyoto Univ.

Beppu-Shimabara Graben located in central Kyushu. In this area, there is north-south extension field. It is important to study the crustal deformation in this area to research tectonics in Kyushu district. We started 20 continuous GPS observation added to GEONET sites from 2009 in and around Beppu-Shimabara Graben.

GPS data observed at our stations, GEONET and 15 IGS sites are analyzed by Bernese GPS Software Ver. 5.0 (Dach et al., 2007) with IGS precise orbit and Earth rotation parameters. We can get daily coordinates of the sites (Nakao, et al., 2010).

Displacement velocities, which are coefficient of linear trend, are estimated by least squares method.

When these velocities, which are relative to 960688 GEONET site, plotted, clear boundary can see. 960688 GEONET site is located in the northern part of Kyushu. The displacement velocities of northern part from this boundary, where fixed site 960688 is located, are almost zero. On the other hand, those of southern part are from several to 10 mm. This boundary is from the northern part of Beppu Bay to Uki City in Kumamoto Prefecture via Aso Volcano. There are a lot of active faults on this boundary. The western part of this boundary seems the south boundary of Beppu-Shimabara Graben. However, the eastern part is not the south boundary but the north boundary.

There is the clear boundary of crustal deformation in Beppu-Shimabara Graben..