Keynote paper

Centenary Geodesy and Seismology Research in Kyoto University, 1909 to 2008

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ABSTRACT

Geophysical research in Kyoto University was started on 1908 when Toshi Shida arrived at Kyoto. He installed tiltmeters and pendulum seismographs at the Kamigamo Geophysical Observatory. With these instruments, he made precise observations of tidal tilts, proposed a third parameter in spherical elasticity, the Shida number, discovered the quadrantal push-pull distribution of the first motion of seismic compressional waves,. verified deep earthquakes, and proposed a plan to detect free oscillation of the Earth. Subsequent original research concerned the first observation of tidal strains by employing extensometers of the Sassa type and development of laser interferometric devices for precise measurements of crustal strains. Kyoto University has contributed to geophysical studies in Thailand through absolute gravity measurements and geographic positioning system observations.

KEYWORDS: Tiltmeter, extensometer, seismograph, gravimeter, geographic positioning system, Shida number

INTRODUCTION

Geophysical research in Kyoto University was started on 1908 when Toshi Shida (1876–1936) got his post as an assistant professor in the Kyoto Imperial University, predecessor of Kyoto University. He graduated from the Institute of Physics of the Imperial University of Tokyo in 1901 and arrived at Kyoto Imperial University in September, 1908. After arriving at Kyoto, Shida immediately installed the tiltmeters of the E von Rebeur-Paschwitz type and the pendulum seismographs of the Wiechert type at the Kamigamo Geophysical Observatory, which was located about 4 kilometers north northwest of from Kyoto University. Shida accomplished many geophysical achievements using data obtained from these instruments. In 1929, Toshi Shida was awarded the 19th Imperial Prize from the Japan Academy on the title of "Investigations on the Rigidity of the Earth and on Earthquake Motions". In addition to his excellent achievements in research and education, Shida established the Beppu Geophysical Observatory in 1924, the Aso Volcanological Observatory in 1928, and the Abuyama Seismological Observatory in 1931. Since then to the present, useful geodetic and seismological data have been obtained in these observatories.

"SHIDA NUMBER" IN EARTH TIDES RESEARCH

Figures 1 shows the general view of the observation room of the Kamigamo Geophysical Observatory and Figure 2 shows the room's arrangement of instruments (Shida, 1912). The observation room stands on a small hill of Paleozoic rock in the northern part of Kyoto city. The Paleozoic rock foundation was excavated to a depth of 3.5 meters over an area 6 meters x 10 meters. The floor of this excavation was covered with concrete 30 centimeters thick except for granite pillars on which instruments were installed.

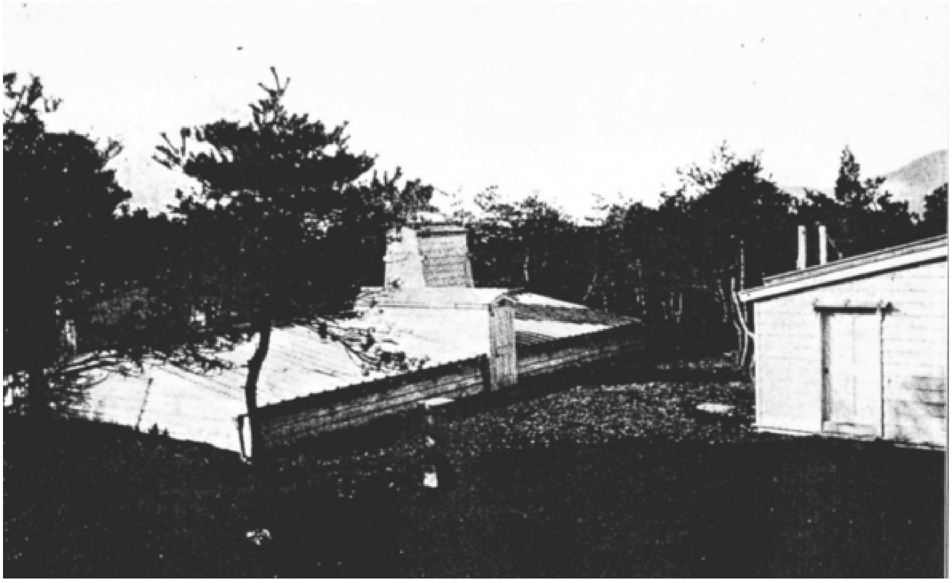

Figure1. General view of the Kamigamo Observatory in 1910 (after Shida,1912).

As shown in the right side of Figure 2, the observation room was divided into two parts by two stone walls across stairs. A vertical seismograph of the Wiechert inverted pendulum type with a 1,300 kilogram weight was installed at the northeast corner of the eastern room. A horizontal seismograph with a 1,000 kilogram weight was installed at the southeast corner of the room. The western room was used for tiltmeter observations.

Shida first observed tidal tilts in Japan. Based on observed data from January 1910 to April 1911, he estimated the diminishing factor, *D*. At first, he was disappointed because *D* values obtained at the Kamigamo Geophysical Observatory were greatly different from those obtained at stations in Europe. This is due to the difference of loading effects of ocean tides. Japan is surrounded by water and the loading effect in Japan is extremely large compared with that in the European continent. He considered this weak point positive and succeeded in estimating the rigidity of Earth's crust from the tidal loading effect at Kamigamo. After eliminating the tidal loading effect, he obtained the diminishing factor value of *D* =0.79, which is similar to values obtained in Europe.

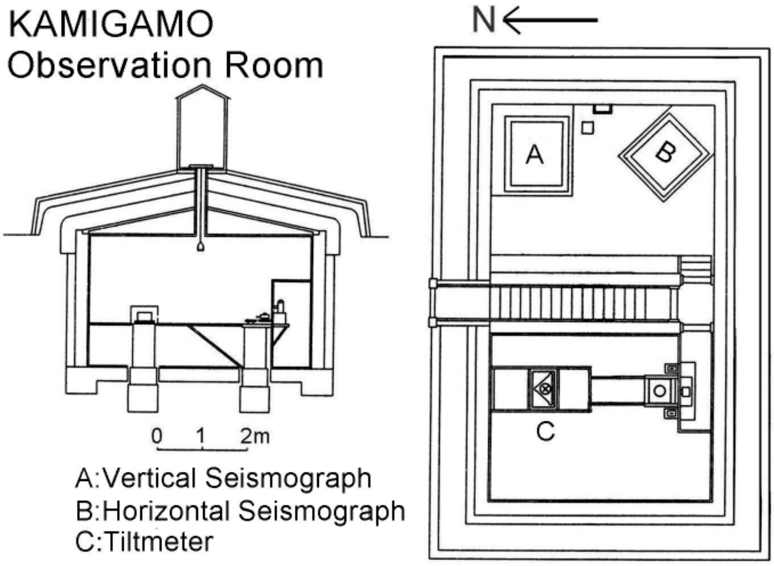

Figure 2. Construction of the observation room and arrangement of instruments (after Shida,1912). Left: side view from west side. Right: plan view.

The name Shida is famous as the Shida Number in tidal studies. The tidal response on the Earth's surface can be represented by three dimensionless parameters in spherical elasticity. They are Love numbers *h* and *k*, and Shida number *l*. Love (1909) showed that the disturbing potential can be represented with sufficient approximation by a spherical harmonic function of the second order and that all the deformations produced in the Earth by this potential may be represented by the same harmonic function multiplied by a numerical coefficient suitable for each aspect of the phenomenon. As the numerical coefficients, Love (1909) introduced two parameters, *h* and *k*. Shida (1912) pointed out that a third number parameter, *l*, should be necessary to obtain a complete representation of the phenomenon. In tidal observations of the solid Earth, *h* is the ratio of the height of the Earth tide to the height of corresponding static ocean tide at the surface. Parameter *k* is the ratio of the additional potential produced by this deformation to the deforming potential. Parameter *l*. is the ratio between the horizontal displacement of the crust and that of the corresponding static ocean tide.

EARLY CONTRIBUTION IN SEISMOLOGICAL RESEARCH

Characteristics of P-Wave First Motions

It is well known that the first impulses of seismic P waves show a quadrantal pattern with compressional or dilatational distribution. This is a simple way to know the earthquake source mechanism. Shida was first to point out this characteristic of P-wave first motions. Based on seismograms obtained at the Kamigamo observatory and other seismic observation networks belonging to the Central Meteorological Observatory of Japan, he found out the quadrantal pattern of P-wave first impulses. This result was first reported at the meeting of the Tokyo Mathematico-Physical Society in April, 1917. A little after this meeting, on May 18, 1917, a destructive shallow earthquake of magnitude 6.3 occurred in Shizuoka Prefecture. .Shida collected seismograms of this earthquake and confirmed that the distribution of P-wave first motions shows a simple pattern of push-pull distribution divided by two orthogonal nodal lines. Figure 3 shows the push-pull distribution of this 1917 Shizuoka earthquake (Shida 1929). This pioneering work has largely contributed to the development of seismology as we know it today.

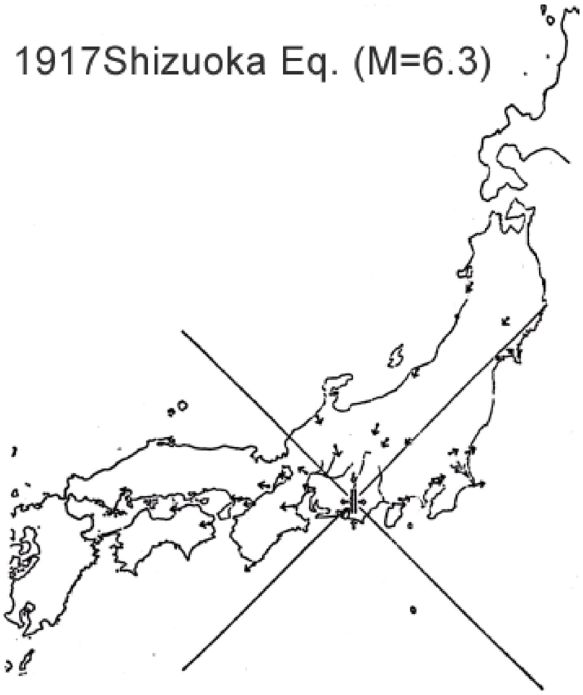

Figure 3. Push-pull distribution of the magnitude 6.3 Shizuoka earthquake of May 18, 1917 (after Shida 1929).

Deep Earthquakes

Deep earthquakes with origins deeper than 60 kilometers are approximately one-quarter of all earthquakes. Existence of deep earthquakes became one of the important grounds to determine the subduction zone in plate tectonics.

As a pioneer in the research of deep earthquakes, Kiyoo Wadati of the Meteorological Agency of Japan is famous for his several papers (Wadati, 1928, 1929, 1931, 1935). He showed convincing evidence of earthquakes occurring deeper than 300 kilometers in and around Japan by employing seismic data obtained from the dense seismic observation network of the Central Meteorological Observatory of Japan. He distinguished the existence of a deep earthquake zone crossing central

Honshu. This zone was later called the Wadati-Benioff zone and is a seismic zone with an inclined surface from the trench toward the continental margin. Based on these achievements, Wadati was awarded the 22nd Imperial Prize from the Japan Academy in 1932.

Prior to Wadati's work, Toshi Shida pointed out the existence of deep earthquakes. Shida examined in detail the arrival times of seismic P waves observed at various stations in Japan under cooperation of Kenzo Sassa. He found some abnormal earthquakes at which the time difference of arrival times among various stations in Japan were very small compared with those of ordinary earthquakes. Moreover, the arrival times of these earthquakes observed at field stations in foreign countries were ten seconds or more earlier compared with those of ordinary earthquakes. Meanwhile, a strong earthquake shook central Honshu on 27 July, 1926. Based on data of P wave initial motions obtained from different stations in Japan, Shida fixed the hypocenter of this earthquake near Lake Biwa, northeast in Kyoto. The depth of the epicenter was determined to be about 260 kilometers. Shida came to the conclusion that deep earthquakes must have taken place in the Earth.

On 28 October, 1926, Shida gave a lecture of deep earthquakes at the opening ceremony of the Beppu Geophysical Laboratory in Kyoto Imperial University. In this lecture, he indicated the deep earthquake zone traversing central Honshu. The reprint of this lecture concerning the deep earthquakes was published ten years later (Shida, 1937). Shida hesitated to publish the result as a scientific paper, so only his lecture note exists. The following comments have been left in his lecture note about this: "The Earth must be statically stable in a zone deeper than 120 kilometers according to the isostatic theory, and it may be difficult to consider that the brittle fractures, such as those occurring near the surface, would occur in the deep zone near the depth of 300 kilometers. Therefore, it is necessary to renew the knowledge of the source mechanism of deep earthquakes and the detailed structure inside the Earth. Time has passed while I was keeping collecting various materials and preparing a high-pressure experiment device to know physical properties in the upper mantle."

First Proposal to Observe Free Oscillations of the Earth

Existence of free oscillations of the elastic Earth had been theoretically predicted since the latter half of the 19th century. However, observational verification of this had to wait until 1960 when the great earthquake of magnitude 9.5 occurred off the west coast of Chili.

In order to observe the free oscillations of the Earth, it is necessary to develop instruments having high sensitivity in the range of periods from several minutes to 1 hour. Ordinary seismographs are not sensitive to such long periods. Before the Chilean earthquake of May 22, 1960, the following effective instruments had been developed: Benioff extensometers (Benioff, 1935, 1959), Press-Ewing long-period seismometers (Press and others, 1958) and LaCoste and Romberg gravimeters (Clarkson and LaCoste, 1957). Use of these instruments provided convincing evidence of Earth's free oscillations in the 1960s.

Prior to this, Toshi Shida designed a new observation system for free oscillations of the Earth in the 1920s. The system was a modified Galitzin's seismometer and consisted of an extremely over-damped 5-minute horizontal pendulum and a double coil galvanometer of low resistance, the needle of which was a Boys quartz fiber torsion balance with a 20-minute period (Shida, 1925). Unfortunately, Shida and his group could not complete the observation system due mainly to financial difficulties.

In the latter half of the 1940s, Maurice Ewing and Frank Press of Columbia University in the United States developed the long-period seismograph (Press and others, 1958). Their device, called the Press-Ewing seismograph, was based on almost the same principle as that proposed by Shida in the first half of 1920s. The Press-Ewing seismograph consisted of a 30-second pendulum and a 90-second galvanometer.

Shida considered a linear extensometer to observe tidal strains and free oscillations of the Earth. This idea was later improved by Kenzo Sassa and Izuo Ozawa and was effectively used to observe the tidal strains of the Earth.

Kenzo Sassa and Izuo Ozawa developed an extensometer using a flexible wire as a length standard to measure the relative displacement between two piers fixed into bedrock (Figure 4). In their device a super-invar wire 1.6 millimeters in diameter is fixed at both ends to concrete piers standing opposite each other at a distance of 20 meters. A 350-gram weight is suspended from the center of this wire by an elinvar wire. Changes in the distance between the two piers cause an up-and-down movement of the weight. This motion is transformed into rotation of the weight through a bifilar suspension consisting of two super-invar wires 0.03 millimeter in diameter. Photographic recording is done with an optical lever using a small mirror mounted on the weight. Using this mechanical-optical extensometer, Sassa and Ozawa first succeeded in observing the tidal strain of the Earth in 1943. They first reported this result at the IAG General Assembly held at Brussels in 1951 (Sassa and others, 1952; Ozawa, 1952)). Thus, the experimental investigation strain-tensor components of Earth tides were started.

APPROACH FOR EARTHQUAKE PREDICTION BY MEANS OF CONTINUOUS MONITORING OF CRUSTAL MOVEMENTS

Continuous monitoring of crustal movements by tiltmeters and strainmeters has been considered to be an effective measure of earthquake precursors, particularly on short time scales of hours to days. An early contribution in such an approach was due to Sassa and Nishimura (1951). They first reported anomalous changes of ground strains and tilts observed before occurrences of some destructive earthquakes at observatories located near the source regions. Among them, a typical example was a precursory tilting motion associated with the 1943 magnitude 7.2 Tottori earthquake. During 6 hours prior to the occurrence of the earthquake, an anomalous tilting motion with the order of 0.1", or 0.5 μ rad., was observed with a tiltmeter of the horizontal pendulum type installed 800 meters underground in the Ikuno mine. This mine was about 60 kilometers from the epicenter. Although there remained some uncertainties to conclude it as a precursor, it played an important role in Japan for promoting the national project for earthquake prediction that started in 1965. Since then, many observatories and supplementary stations for monitoring crustal movements have been established in Japan. More than 100 stations are operating under the national project for earthquake prediction. Despite such a dense arrangement of stations equipped with improved instruments, reliable precursors immediately before the occurrence of earthquakes are not able to be detected.

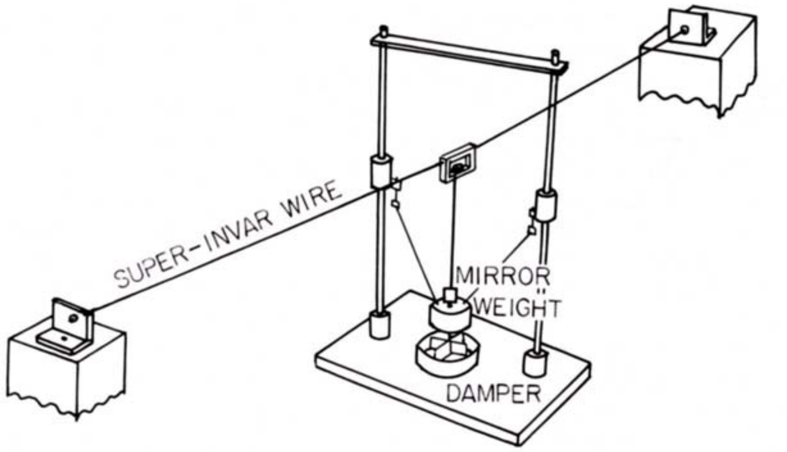

Figure 4. Schematic representation of a wire extensometer of the Sassa type.

In the early morning of January 17, 1995, a destructive magnitude 6.9 earthquake occurred near the city of Kobe. The death toll from this earthquake was more than 6,300 and was due to collapse of buildings and bridges, fire, and disease. Continuous observation of crustal strains, using a laser strainmeter, have been made at the Rokko-Takao station in Kobe since 1989 (Takemoto and others, 2003). The distance from this station to the earthquakes' epicenter is about 20 kilometers and the station is located almost above the fault plane. Anomalous strain changes before and after the earthquake were looked for using laser strainmeter data, the main focus being the period of one week before the earthquake. No distinct evidence was found (Takemoto and others, 1998a). Finding reliable precursors immediately before the occurrence of earthquakes from continuous monitoring of crustal movements by tiltmeters and strainmeters will be difficult.

APPLICATION OF LASER INTERFEROMETRIC DEVICES TO PRECISE MEASUREMENTS OF CRUSTAL DEFORMATION

In order to observe crustal deformations, various types of extensometers were developed during the last half of 20th century (Sassa and others, 1952; Benioff, 1959). These meters essentially use solid material of low thermal conductivity as a length standard for measuring a relative displacement between two piers fixed into bedrock (Figure 4). Fused quartz tubes or super-invar wires are commonly used as the length standard.

The appearance of the laser at the beginning of the 1960s opened up new possibilities in crustal strain measurements. Interferometric strainmeters were developed that used a coherent and stable laser source (Berger and Lovberg, 1969). The laser interferometric strainmeter enables a small strain to be measured quantitatively in terms of the wavelength of the laser light without using a length standard of any solid materials.

In Kyoto University, the laser interferometric device was used for calibrating conventional rod-type extensometers at first. Later, laser strainmeters of the Michelson type were installed at the Amagase Crustal Movement Observatory in Kyoto in 1977 (Takemoto, 1979). The same type laser strainmeter was installed at the Rokko-Takao station in 1988 (Takemoto and others, 1998a). Although precursory strain changes could not be detected before the earthquake of January 17, 1995, the fluid core resonance could be estimated using data of the laser strainmeter installed at the Rokko-Takao tunnel in Kobe (Mukai and others, 2004).

In 2002, a 100-meter laser strainmeter system was installed in a deep tunnel about 1,000 meters below the surface at the Kamioka mine, Gifu, Japan (Figure 5). The system consists of three types of independent interferometers: an east-west linear strainmeter of the Michelson type with unequal arms, a north-south and east-west differential strainmeter of the Michelson type with equal arms, and a north-south absolute strainmeter of the Fabry-Perot type (Figure 6). These strainmeters are configured in L-shaped vacuum pipes, each of which has a length of 100 meters. The two Michelson types are highly sensitive, in the order of 10^{-13} strain, and have wide dynamical range, 10^{-13} -10^{-6}. The Fabry-Perot type is a new device for absolute-length measurements of the order of 10^{-9} of a long base line, 100 meters, Fabry-Perot cavity by using phase-modulated light (Takemoto and others, 2004, 2006a). The laser source of both Michelson type strainmeters is a frequency-doubled YAG laser having a wavelength of 532 nm. The laser frequency is locked onto an iodine absorption line and a stability of 2×10^{-13} is attained. The Fabry-Perot type uses another laser source of the same type as used for the two Michelson types. The light paths of the laser strainmeter system are enclosed in SUS304 stainless steel pipes. The inside pressure is kept at 10^{-4} Pascal. Consequently, quantitative measurement of crustal strains of the order of 10^{-13} can be attained by employing the laser strainmeter system of the two Michelson types at Kamioka. This resolving power corresponds to that of a superconducting gravimeter. The noise level recorded at Kamioka is lowest, in the range of 10^{-3} to 10^{-1} hertz, among laser strainmeters now operating in the world.

Figure 5. The 100 -meter laser strainmeter system in the Kamioka.mine, Gifu, Japan.

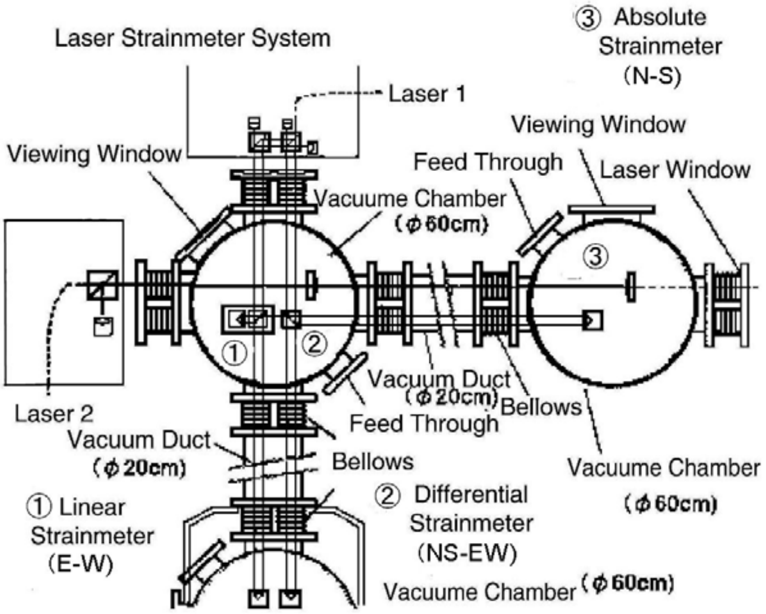

Figure 6. Schematic view of the laser strainmeter system at Kamioka, consisting of three types of laser interferometers. Number 1 is a simple Michelson type interferometer of unequal arms installed in an east-west direction. Number 2 is an equal-arm laser interferometer detecting difference of linear strains in both north-south and east-west directions. Number 3 is a Fabry-Perot type absolute interferometer installed in a north-south direction.

Figure 7 shows the strain seismograms obtained from the two Kamioka Michelson type laser strainmeters at the time of the great Sumatra-Andaman earthquake of December 26, 2004. The left side is high-passed and the right side is low-passed, 1,000 seconds, records. We can recognize that The maximum amplitude of the seismic wave on the left graph is in the order of 1 micro strain and the coseismic strain step is in the order of 1 nano strain at the epicentral distance of 5600 kilometers.

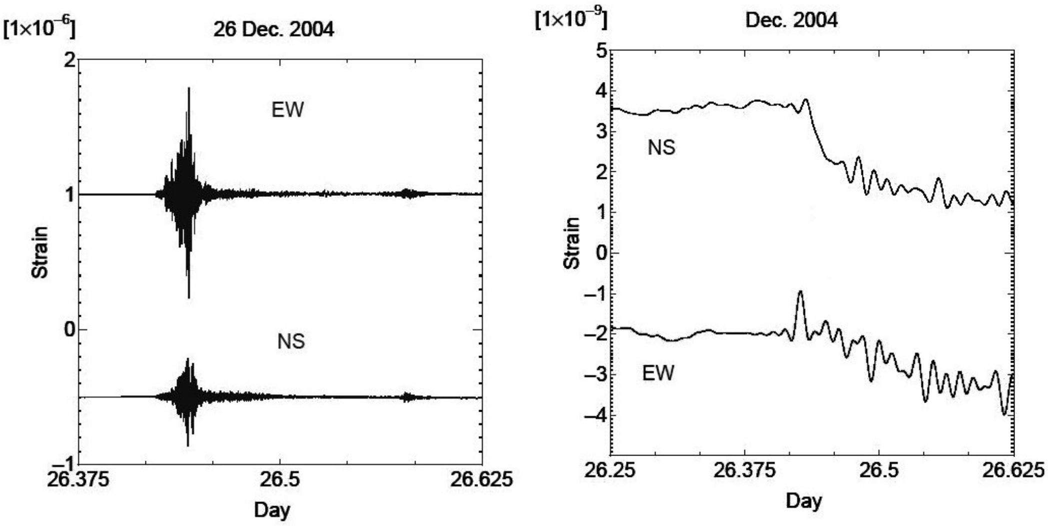

Figure 7. Strain seismograms of the great Sumatra-Andaman earthquake of December 26, 2004, observed at Kamioka.

A new technique based on holographic interferometry was developed for measuring crustal deformations (Takemoto, 1986, 1990). The holographic recording system, consisting of an He-Ne gas laser and associated optical elements, was first installed in a tunnel at the Amagase Crustal Movement Observatory in 1984. Tunnel deformations caused by tidal and tectonic forces were precisely determined using real-time technique of holographic interferometry. In this procedure, a hologram of the tunnel wall within a section 1 to 2 meters in diameter was directly recorded on a photographic plate and then the plate was carefully reset in the same position at which the hologram had been taken. When the reconstructed image of the hologram was superimposed on the current image of the tunnel wall, many interferometric fringes could be seen through the hologram. The fringe displacement, formed by the deformation of the tunnel, was continuously recorded on a video cassette tape using a video camera and a time-lapse video recorder. The change in the fringe patterns was analyzed using the image-processing system. Tidal deformations obtained from the holographic method were consistent with the strain changes observed with laser strainmeters in the same tunnel. These observational results substantiated the tunnel deformation estimated by finite-element calculations.

The holographic system, however, has a margin for improvement in use of long-term strain measurements because the fringe pattern observed through the photographic plate gradually blurs over time. Thus, a clear record of holographic interferometry cannot be obtained, even over a week. Therefore to overcome this limitation, the Electronic Speckle Pattern Interferometry technique, in which the interference fringe pattern can be produced by using electronic processing, was tried

(Takemoto and others, 1998b). This attempt, however, did not succeed due to technical difficulty in detecting slowly moving crustal deformation.

CONTRIBUTION OF KYOTO UNIVERSITY TO GEOPHYSICAL STUDIES IN THAILAND

Dr. Michio Hashizume, Senior Programme Specialist of the UNESCO Office in Jakarta moved to Chulalongkorn University in 1998 and contributed to activating geophysical studies at the university. He graduated from the Department of Geophysics, Faculty of Science, Kyoto University in 1961. He was able to open a satellite office, the Kyoto University Active Geosphere Investigations 121 project, at Chulalongkorn University in 2004. This office is one of the projects of the 21st Century Center of Excellence Program in Japan. Hashizume also contributed to the establishment of the Observatory for Atmospheric Research at Phimai in 2004.

Taking part in the KAGI21 project and the Asia-Pacific Space Geodynamics project cooperation campaigns in the International Association of Geodesy, we have established the Absolute Gravity Standard Station network in East Asia and Southeast Asia with FG-5 absolute gravimeters (Takemoto and others, .2006b, 2006c). During the period from 2002 to 2005, we determined absolute gravity values in the order of microGals at 30 stations in China, Taiwan, Indonesia, Malaysia, Thailand, the Philippines, and Japan. In Thailand, we carried out absolute gravity measurements in Bangkok and Chiang Mai using absolute gravimeter FG-5 no. 210 in cooperation with Chulalongkorn University and Chang Mai University in September 2005. In Chang Mai, a Chinese group had carried out absolute gravity measurements at the same station in January 2001 by employing the NIM-II absolute gravimeter (Guo and others, 1982). We, thus, compared our result with that previously obtained by the NIM-II gravimeter in 2001. The difference between the two results is only 9 microGals during a period of 4.5 years (Takemoto and others, 2006b). This means that Chang Mai is relatively stable in the sense of tectonic activity.

We have been conducting continuous geographic positioning system observations in Thailand since 2004 in collaboration of Kyoto University and Chulalongkorn University. After the Sumatra-Andaman earthquake of December 26, 2004, Hashimoto and others (2006) analyzed geographic positioning system data from 27 stations in Asia and Oceania and estimated crustal deformations associated with the earthquake. At the Phuket station, about 600 kilometers from the epicenter, a large coseismic displacement of about 26 centimeters, 24 centimeters to the west and 10 centimeter to the south, was detected. The coseismic displacement at the Bangkok station was 6.2 centimeters to the west and 3.8 centimeters to the south. The Cheng Mai station moved 1.4 centimeters to the west and 2.1centimeters to the south.

Recently, we succeeded in observing seismic surface waves by employing geographic positioning system phase data sampled basically at 1 Hertz. On May 12, 2008, a destructive magnitude 7.p earthquake occurred in Sichuan, China. At the time of the occurrence (May 12, 2008, 6:28:01(UTC), the Nong Khai, Sri Samrong, and Phimai geographic positioning system stations were in operation. Manabu Hashimoto of the Disaster Prevention Research Institute, Kyoto University, analyzed the data of these three stations in conjunction with high rate data from the Wuhan, Shanghai, and Quezon City IGS sites. For his analysis, GpsTools program developed by Tomoji Takasu was used. Figure 8 is an example of this type analysis and shows the result at Phimai after applying a band-pass filter with 0.003 to 1 Hertz to original data. In this figure, wave trains arrive around 6:35 - 6:40. These are considered to be Love waves, since transverse components arrived faster than radial ones. Considering azimuth, the east-west component corresponds to transverse in Thailand. These wave trains show clear dispersion. This observational result shows the possibility of using the geographic positioning system as the long-period seismograph.

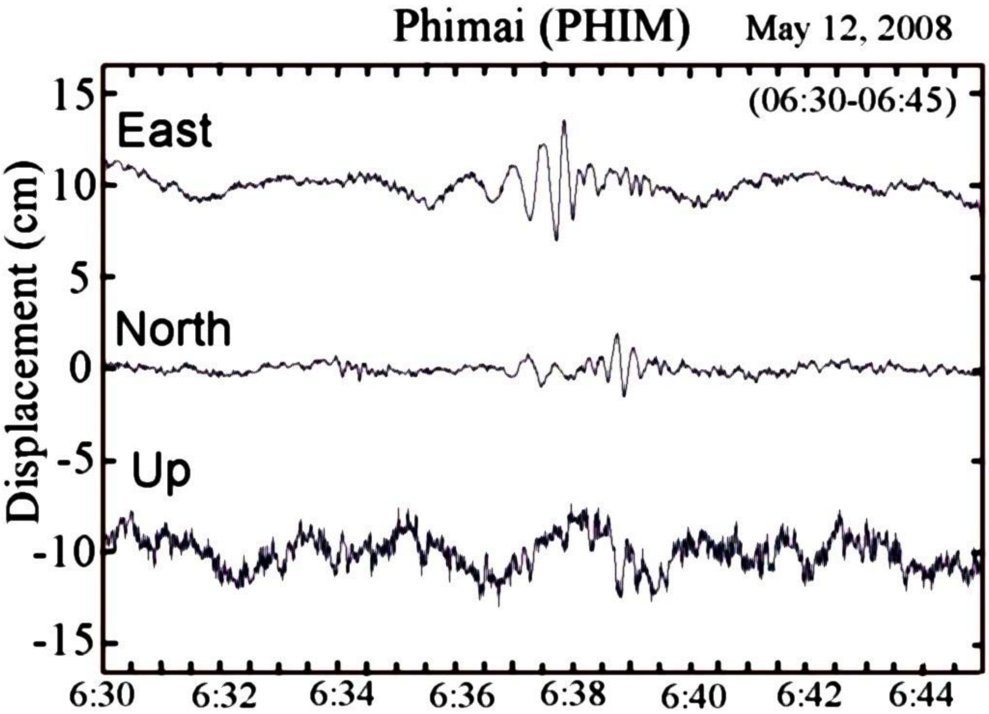

Figure 8. Record of seismic waves observed with 1 Hz GPS at Phimai during the time period from UT6:30 to 6:45 on May 12, 2008. Horizontal axis is time, one division is 30 seconds. From the top, east-west, north-south and up-down components are shown, respectively.

ACKNOWLEDGEMENT

The author is grateful to Michio Hashizume and Manabu Hashimoto for their cooperation and useful comments.

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