MONITORING OF CRUSTAL DEFORMATION AND ITS APPLICATION TO MITIGATION OF EARTHQUAKE DISASTERS

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This paper deals with the potential of GEONET, GNSS Earth Observation Network as a tool to mitigate earthquake disasters. GEONET presents spatiotemporal information on crustal deformations due to seismic forces, thus it has possible applications to earthquake engineering both in space and time. This paper discusses, as a temporal application, the precursory behaviors of the crust found prior to the 2011 off the Pacific Coast of Tohoku Earthquake to enhance the actual capability of earthquake prediction from engineering viewpoints. The GEONET data also can obtain coseismic crustal deformations closely related with tsunami resulting from a huge interplate earthquake. This paper describes, as a second application, the potential use of GEONET for early warning system against tsunami propagation. The coseismic deformations of the crust also exert another influence on earthquake damage to large-scale structures as a result of spatial differential of displacements, inducing seismic strains within structural bodies. This paper finally discusses, as a third application of the GEONET data, the seismic strain characteristics of ground derived from coseismic crustal deformations, relating them with earthquake damage to civil engineering structures.

Key Words : *GNSS, crustal deformation, GEONET, earthquake prediction, early warning of tsunami propagation, coseismic strains of ground, earthquake damage analysis*

1. INTRODUCTION

Earthquake-related observation systems in Japan have been drastically enhanced with the miserable damage experiences caused by the 1995 Kobe Earthquake¹. Two of the most representative examples of these systems are K-NET and KiK-net both of which are observation systems of strong ground motions during earthquakes in and around Japan². The observed data due to both systems are extensively used nowadays and have been contributing worldwide to earthquake engineering studies. An-

other example, which has been also broadly installed after the Kobe Earthquake and is important to engineering application, is GEONET, GNSS Earth Observation Network³. Here, GNSS (Global Navigation Satellite System) is a technical term newly emerged after GPS (Global Positioning System). GEONET is a comprehensive system for positioning and monitoring crustal deformations of the Japanese islands using the GNSS technology (continuous GNSS). Nowadays GEONET observation stations have been deployed at over 1,000 sites throughout Japan and their observed data are widely

available to the public through the Geospatial Information Authority of Japan, GSI⁴⁾.

Both observation systems of strong motions and crustal deformations might have complementary roles to each other in studying earthquake disaster phenomena. The latter, however, has been less used in the earthquake engineering field compared with the former. The reason is that earthquake damage has been considered to be attributable to inertia force subjected to structures, and a strong-motion observation system gives vector information on acceleration data related directly with inertia force. Although inertia force exerts some important effects on earthquake damage, it is still a scientific concern to determine what kind of physical force is essential to decide earthquake damage to structures. The vector data of acceleration motion might be a key factor to cause damage to simple mass structures, whereas tensor data such as strains and stresses might have a decisive effect on structures with extensive configuration in space. If we place emphasis on strains or stresses induced within ground or structures during earthquakes, observation systems of crustal deformations such as GEONET become important tools because of their observable data.

The purpose of this paper is to discuss the engineering potential of the GEONET data applicable to mitigate earthquake disasters. The GEONET data basically provide spatiotemporal information on crustal deformations due to seismic forces, thus various applications might be possible in space and time to deal with earthquake disasters. This paper discusses three applications: (1) the application to earthquake prediction using temporal variations in crustal deformation; (2) the application to tsunami early warning with the use of coseismic information on crustal deformation; and (3) the application to damage analysis to civil engineering structures using coseismic strains of ground derived from crustal deformation, which were all hinted from the 2011 off the Pacific Coast of Tohoku Earthquake (the 2011 Great East Japan Earthquake)⁵⁾. In this paper, we intend to highlight the importance of the three applications in engineering, while comprehensively reviewing our published papers^{6),7)} and revising them.

2. POSSIBLE APPLICATIONS OF GEONET DATA TO ENGINEERING

(1) Introduction to the GEONET system

As previously described, the GEONET system was officially established in the wake of the disastrous experiences during the 1995 Kobe Earthquake. Since 1995, the number of its observation stations

has increased year by year and now it amounts, as of 2016, to about 1300 stations deployed over Japan. Its average station-to-station distance is 20~25 km and GSI has been supervising its total system providing various data obtained by the system⁸⁾. The data-sampling rate of GEONET has also improved year by year and a one-second rate has been realized nowadays. **Figure 1** shows the GEONET observation stations in east Japan.

In previous years, geodetic data leading to crustal deformation were obtained by the literally ground-crawling efforts of surveying at the earth surface. Contrary to such an old manner, satellite technology, such as the GNSS technique, has basically changed geodetic survey. The GNSS technique has nowadays enabled geodetic surveying for a millimeter to centimeter level of positioning. The accurate positioning methods by GNSS are roughly divided into two categories: the differential GPS positioning (DGPS) method and the precise point positioning (PPP) method^{9),10)}. The DGPS method requires access to the observations of one or more reference stations with known coordinates, while the PPP technique needs only a single observation station for obtaining GNSS satellite data. The PPP method, on the other hand, requires precise satellite orbits and clocks, meaning that the two methods have both advantages and disadvantages.

In order to achieve positioning of coordinates, in general, users have to carry out complicated calculations of either the DGPS or PPP techniques using

Fig.1 Map of observation stations of GEONET.

observed data of GNSS satellites. Such calculation processes, however, are laborious, so that many institutes throughout the world provide positioning data processed by either technique, which are generally called “the products,” as well as raw GNSS satellite data that have the so-called RINEX format⁹⁾. GEONET also provides the products of processed positioning data together with the RINEX data from each observation station. The positioning products resulting from the GEONET analyses are available in different forms such as Q3, R3, and F3 solutions with different accuracy¹¹⁾. Among them, the F3 solution is the most accurate one giving the absolute position of the observation station. GSI calls the F3 solution of data “the daily coordinates at the GEONET observation station.” The F3 solution, which is processed daily at 12:00:00 of the Coordinated Universal Time, UTC, is available through the GSI website. The authors developed a software system that automatically downloads the F3 solution data through internet and serially treats them to plot various figures¹²⁾.

(2) Brief overview of past studies on the application of GNSS data

GNSS data have been used mainly in the geophysical fields, especially geodesy, reflecting their observables closely related with the movements of land¹³⁾. Seismology is also another pioneering academic field that uses GNSS data because various seismic information such as faulting source parameters, ground motions, and so on result from GNSS observables¹⁴⁾. In recent years, especially, inverse analyses on seismic faulting source using GNSS data have become routine work to investigate faulting mechanism and seismic source parameters¹⁵⁾. In addition, kinematic analyses of GNSS data have begun to play an essential role in seismology to obtain extremely long-period motions of ground¹⁶⁾. The number of these seismological researches using GNSS data, the so-called seismogeodetic research, has drastically increased through the 2011 Great East Japan Earthquake¹⁷⁾. The remarkably disastrous event provided us with an opportunity to recognize a potential of the GEONET system not only in the academic fields but also in the social countermeasures to mitigate earthquake disasters. The huge interplate earthquake triggered a large tsunami reaching a maximum wave height of some 40m, resulting in disastrous damage to the Pacific coastal areas in east Japan. Immediately after the earthquake, the GEONET system started to attract attention as an effective tool for early warning measures to tsunami propagation because deformations of the crust are closely related with tsunami generation¹⁷⁾. This paper also discusses the application of the GEONET

data to tsunami propagation.

In earthquake prediction, on the other hand, crustal deformations have been originally considered to be a key datum to detect a precursor of earthquake occurrence, represented by Mogi’s study¹⁸⁾. Stimulated by many studies like the Mogi study, the GNSS data have played an important role in the earthquake prediction field. Contrary to such expectations from the academic and social fields, however, continuous GNSS systems including GEONET have not yet officially succeeded in earthquake prediction probably because of complicated mechanisms of earthquake occurrence and, at the same time, insufficient research efforts. The failure of earthquake prediction against the 2011 Great East Japan Earthquake, especially, resulted in severe social criticisms to the Seismological Society of Japan (SSJ) that has been principally specializing in earthquake prediction. In response to such a social reflection, the SSJ published an official announcement expressing that earthquake prediction is impossible at present and so is the use of an exact warning system to serve society¹⁹⁾. Historically, earthquake prediction studies in Japan have been carried out exclusively in the science field represented by the SSJ. Actually, however, earthquake prediction might be an essential theme in the engineering/technology field because it requires a technical judgment deeply related with social activities to prevent and mitigate earthquake disasters. It might have been abnormal in the Japanese academic societies that engineers have not been involved in the works of earthquake prediction. In this paper, we investigate in detail the pre-earthquake behaviors of the crust before the 2011 Great East Japan Earthquake from the engineering viewpoint using the GEONET data. As for the seismogeodetic research using the GEONET data for the 2011 Great East Japan Earthquake, many people, including the GSI researchers, published their respective papers²⁰⁾. In this paper, we also intend to make similar analyses from our independent standpoint. Although they are retroactive investigations, a future potential of the GEONET data contributable to earthquake prediction is discussed.

In the earthquake engineering field, the GNSS data have recently attracted attention from many areas, for example: (1) the “fling step vibration” study of structure response during earthquake motions²¹⁾; (2) the ground sliding study²²⁾; and (3) the structural displacement of high-rise building²³⁾. Similarly to the ground sliding study, the GNSS data have a potential to achieve studies on ground failure including slope damage and studies on seismic failures of structures having extensive configuration in space. This paper also discusses earthquake

damage on ground and structures associated with seismic strains in ground derived from the GEONET data.

3. CRUSTAL DEFORMATION DUE TO GEONET DATA

(1) Coseismic crustal deformation due to the 2011 Great East Japan Earthquake

Figure 2 shows the temporal records of latitude, longitude, and elevation of the F3 positioning data obtained over the past 10 years prior to the 2011 Great East Japan Earthquake at a representative observation station of GEONET, Shizugawa, whose position is shown in **Fig.1**. **Figure 2** also presents the occurrence dates of five damage-causing earthquakes including the 2011 Great East Japan Earthquake during the same period. It clearly illustrates that the 2011 Great East Japan Earthquake induced conspicuously greater crustal movements compared with the other earthquakes. From the F3 data of GEONET, it is possible to numerically obtain the coseismic movements of each station due to an earthquake by calculating the differences in absolute positions before and after the event. In order to obtain such coseismic movements, we need displacement data obtained with respect to a reference site that is dealt with as a fixed position because the F3 solution is a product processed by a method including the DGPS technique. Here, we call such a method of obtaining displacement “the fixed method” or “the fixed treatment.” We set the Misumi station (station number 950388) in Shimane Prefecture as reference because of its long distance from the epicenter of the 2011 Great East Japan Earthquake. At the same time, we need to determine here the reference times before and after the relevant earthquake. The official occurrence time of the 2011 Great East Japan Earthquake was 05:46:18 (UTC) on 11 March 2011, thus, the reference times for the pre- and post-earthquake conditions of the F3 data were set up, respectively, to be 12:00:00 (UTC) on 10 March and 12:00:00 (UTC) on 12 March. We obtained numerically the displacements in the three directions of longitude, latitude, and elevation at each observation station of GEONET using the three directional coordinates at these pre- and post-earthquake times.

Figure 3 shows the distributions of the horizontal and vertical displacements obtained. Both vectors of displacements were plotted in terms of logarithmic scale divided by a constant value to avoid overlapping of vector traces and to clearly express their directions and absolute values that are distributed broadly ranging from a large level of meter to a

Fig.2 Time variations of latitude, longitude and height over the past 10 years at Shizugawa. Upper:latitude, Middle:longitude, Lower:height.

small one of centimeter. The standard scale of logarithmic values is shown in **Fig.3**. At the same time, contour lines of absolute values are plotted in **Fig.3** to clearly show the distribution trend. Note here that the contour lines are scaled by taking the logarithm of displacement (mm) and dividing the logarithmic value by a constant of 4. It is obvious at a glance in **Fig.3** that the Honshu island of Japan moved greatly amounting to some 5 m and 1 m in the horizontal and vertical directions, respectively, at some sites. The horizontal displacements occurred roughly toward the epicenter showing concentric circles of contour for their absolute values, whereas the vertical ones showed subsidence and upheaval of land mainly depending on epicentral distance. These coseismic crustal deformations are closely related with various engineering and social problems such as structural damage, ground failures, tsunami propagation, post-earthquake restoration works, and so on. Some problems of these are dealt with in later sections of this paper.

Fig.3 Coseismic crustal deformations obtained by GEONET.
Left: horizontal component, Right: vertical component.

(2) Pre-seismic movements of the crust prior to the 2011 Great East Japan Earthquake: Long-term and mid-term precursor to the earthquake

It is natural that pre-seismic movements are not clearly identified in **Fig.2** because they were much smaller than the coseismic movements. In order to focus on the pre-seismic movements, the time variations are enlarged in the vertical axes of the three coordinates as shown in **Fig.4**. **Figure 4** does indicate that there are clear long-term trends in each coordinate: (1) a gradual displacement toward south in the latitudinal direction; (2) a gradual displacement toward west in the longitudinal direction; and (3) a small variation in the vertical direction. These long-term variations, especially the gradual movements in the longitude direction, might have resulted from the interaction between the movements of the plates surrounding Japan such as the Pacific Plate and North American Plate. **Figure 4** also shows abrupt coseismic changes in the damage-causing earthquakes: they have a tendency to show zigzag movements reversely against the behavior of the preceding or following earthquakes.

Medium-term pre-seismic movements of the crust prior to the 2011 Great East Japan Earthquake were further investigated by plotting temporal variations in the three coordinates for a period of about one

year before the earthquake as shown in **Fig.5**. Although not so clear, one may recognize that the long-term trend of temporal variations toward south in latitude stops around six months before the earthquake, showing a flat trend. The westward long-term trend of longitude variations also stopped about two months before the earthquake. The variation trend in elevation showed less changes. **Figure 5** suggests that some medium-term pre-seismic movements of the crust might have occurred during several months before the 2011 Great East Japan Earthquake.

(3) Pre-seismic movements of the crust prior to the 2011 Great East Japan Earthquake: Short-term precursor to the earthquake

Figure 6 shows temporal variations in latitude, longitude, and elevation for a period of about 10 days before the 2011 Great East Japan Earthquake. **Figure 6** also indicates day stamps to clearly show the daily variations. The time variations in movements are different depending on direction, but the longitudinal direction indicates a remarkable precursory eastward variation, that is, an increasing trend to the east, starting around 7~8 March and culminating in the final stage on 11 March. **Figure 6** shows the result obtained only at a particular observation station, Shizugawa shown in **Fig.1**. Similar

movements of the crust simultaneously occurred at other observation stations. To show such results at many observation stations, we need displacements obtained by the fixed treatment for a reference observation station as mentioned previously. The displacements at all the stations were numerically obtained by the fixed method of the reference station of Misumi similarly to the coseismic displacements in **Fig.3**. **Figure 7** shows the locations of the eight representative observation stations near the epicenter of the earthquake, whose time variations in displacements are simultaneously compared. **Figure 7** also presents the epicenters of the mainshock and the largest foreshock, which occurred with a magnitude of 7.3 on 9 March. The temporal variations in displacements at these observation stations in the respective direction of east west (EW), north south (NS) and up down (UD) for a period of some 10

days before the 2011 Great East Japan Earthquake are plotted in **Fig.8**. Note in **Fig.8** that the displacements in each direction were obtained cumulatively starting from the reference time of 1 January 2003. The time-varying trends of displacements at each observation station in **Fig.8** are similar to those in **Fig.6**. Particularly, the EW component shows similar increasing trends to east starting around 7~8 March at each site while the NS component has opposite increasing trend to north or south depending on site around the same period. Contrary to the horizontal components of displacement, the UD component shows less characteristic variations in time at each site. These temporal variations in displacement might suggest that some pre-seismic phenomena related with the so-called pre-slip of faulting source existed for the horizontal component in the 2011 Great East Japan Earthquake.

Fig.4 Time variations of latitude, longitude and height over the past 10 years at Shizugawa. Enlarged in the vertical axes for each figure.
Upper:latitude, Midel:longitude, Lower:height.

Fig.5 Time variations of latitude, longitude and height over the past one year at Shizugawa. Enlarged in the vertical axes for each figure,
Upper:latitude, Middle:longitude, Lower:height.

Fig.6 Time variations of latitude, longitude and height over the past 10 days at Shizugawa. Enlarged in the vertical axes for each figure. Upper:latitude, Middle:longitude, Lower:height.

Fig.8 Time variations of displacements over the past 10 days at 8 observation stations of GEONET. Upper:NS, Middle:EW, Lower:UD.

Fig.7 Map of observation stations of GEONET.

As to the clear trend of displacements in the EW direction, an alternative interpretation was presented that they are not the pre-seismic phenomena for the

mainshock on 11 March, but the post-seismic movements of the largest foreshock on 9 March (Suito et al. 2012)²⁴. It is difficult to definitely judge which interpretation is correct at this stage. Another parameter of time variations, the azimuth of the displacement vector, however, may provide a clue for this problem. **Figure 9** shows the daily variations in the azimuth for the horizontal component's vector of displacements plotted in **Fig.8**, which is measured counter-clockwise from the east base line, at each observation site for the same period as in **Fig.8**. **Figure 9** demonstrates that the daily variations in the azimuth tend to stabilize after the mainshock on 11 March, whereas the azimuths continually increase from around 8 March to 11 March without stabilizing after 9 March when the largest foreshock occurred. Especially the increasing trends of the azimuth are more remarkable from 9 March to 10 March, which is a post-seismic period for the M7.3 largest foreshock, than the ones from 8 March

Fig.9 Daily variations of azimuth over the past 10 days at 8 observation stations of GEONET.

to 9 March. Post-seismic variations after a shock may be smaller in magnitude compared with variations due to the shock itself. This interpretation leads to a judgment that the increasing trends of the azimuth in **Fig.9** provide a pre-seismic sign before the 2011 Great East Japan Earthquake rather than a post-seismic sign after the largest foreshock. This may mean that the time-varying trend of the azimuth can be an effective parameter to judge whether some variations are pre-seismic or post-seismic. The stability of displacement azimuth after the mainshock should be further studied for many earthquakes, but characteristic time variations in the azimuth in **Fig.9** at least suggest that those changes were a short-term precursory phenomenon to the occurrence of the 2011 Great East Japan Earthquake.

In addition to the above precursory phenomena found about three days prior to the earthquake, more imminent pre-earthquake behaviors of the crust were also detected by GEONET: a pre-seismic phenomenon existed for the temporal variations in displacements and azimuth even during a few hours immediately before the 2011 Great East Japan Earthquake⁶⁾. See the details in Reference 6.

As opposed to the abovementioned understanding for the precursory behaviors of the crust before the 2011 Great East Japan Earthquake, there have been a number of papers denying and/or doubting such a precursor^{20), 24)}. These papers, including our present one, were based on some limited data and information, even if they stand at either stance of denying or supporting. Accordingly, we need further efforts to achieve our purpose of earthquake prediction using a variety of technique and data. Anyway, the GEONET system is expected to make an im-

portant contribution for the final purpose.

4. RELATION OF THE COSEISMIC CRUSTAL DEFORMATION WITH TSUNAMI HEIGHT

(1) Tsunami propagation by the 2011 Great East Japan Earthquake and its relation with coseismic deformation of the crust

The 2011 Great East Japan Earthquake triggered a huge tsunami against vast areas mainly including the Pacific Coast in east Japan. The Japan Meteorological Agency, JMA, issued a warning of tsunami propagation immediately after the earthquake occurrence. Regrettably, however, the early warning could not function so as to fully decrease the number of fatalities and missing victims²⁵⁾. This prompted an effective countermeasure necessary to enhance the estimation of propagating tsunami height due to interplate earthquakes. GEONET is now considered to play a central role for such a need²⁶⁾. Here, we discuss the relation between the tsunami propagation and coseismic deformation of the crust during the 2011 Great East Japan Earthquake based on our original analyses of the GEONET data.

Many institutes and groups of researchers conducted on-the-spot investigations about the wave height of tsunami propagating to each coastal area and compiled reports. Among them, the report compiled by the 2011 Tohoku Earthquake Tsunami Joint Survey Group²⁷⁾ might be the most comprehensive. The results investigated by the group are reproduced in **Fig.10** to compare with the coseismic crustal deformations obtained by our analyses (See the verti-

Fig.10 Comparison between tsunami height and coseismic crustal deformation in the vertical direction. Left: map of tsunami sites, Middle: height of tsunami, Right: map of coseismic vertical deformation. Left and middle figures are cited from reference 27.

Fig.11 Scatter diagram of tsunami height and vertical displacement (subsidence) of ground. Blue line: fitting line by linear regression analysis. r: correlation coefficient of the line.

cal component of crustal deformations in **Fig.3**). The coseismic crustal deformations in the vertical direction are plotted in **Fig.10**, as a color-image map, to clearly show the spatial distribution of deformation largeness. **Figure 10** presents both heights of inundation and run-up of the propagating tsunami along the coast and arranges the latitude scale common to both distributions of the tsunami

and coseismic deformations of the crust. **Figure 10** can compare the spatial distribution of the propagating height of tsunami with the one of coseismic crustal deformation along the coastline, indicating that there is a fairly good similarity between both spatial variations in tsunami height and crustal deformation of vertical component. **Figure 10** presents a qualitative comparison between both distributions, but we need more quantitative discussion to show a good correlation between propagating tsunami and coseismic deformation of the crust. Besides the above Joint Survey Group, JMA also compiled in detail its original surveyed data of tsunami propagation at representative sites along the Pacific Coast in east Japan²⁸). The JMA investigation, which is based on on-the-spot surveys of various traces of the traveling tsunami, presents numerical data of inundation heights and site positions. Especially, the exact position data of site enable us to make a numerical comparison between the tsunami inundation heights and coseismic deformations of the crust obtained by GEONET. **Figure 11** shows a scatter diagram correlating the JMA tsunami heights with the crustal subsidence at representative sites of GEONET that are located next to each JMA survey site. A fitting line, which was obtained numerically using the linear regression analysis, is also drawn in **Fig.11**. **Figure 11** demonstrates a clearly proportional trend of the tsunami height with the crustal subsidence, giving a high correlation coefficient of 0.81 for the fitting line. This implies that the subsidence of the

crust at coastal sites locally amplified the traveling tsunami waves. It is well known that the topographical forms, depth of sea bottom, and other local factors around coastal areas can exert strong influence on the amplitude of tsunami traveling toward coast. In addition to such local site factors, **Fig.11** shows that the subsidence of coastal land due to coseismic crustal deformation gives another amplification effect on tsunami waves.

(2) Theoretical estimate of coseismic crustal deformation using the faulting source model

In order to use the information of coseismic crustal deformations by GEONET as a tsunami warning system, the correlation between coseismic deformation of the crust and tsunami generation should be theoretically validated. **Figure 12** shows the distribution maps of the displacement vectors theoretically estimated for the 2011 Great East Japan Earthquake using the dislocation theory by Okada²⁹⁾. The Okada theory has been coded into many software such as the “Coulomb”, “3d-def,” and so on^{30),31)}. Here, we employed the 3d-def program originally coded by Gomberg and Ellis³¹⁾ and modified by us so as to easily estimate crustal deformations due to the 2011 Great East Japan Earthquake. As for the earthquake, many researchers have inferred fault-plane solutions of seismic source based on various methods³²⁾. In reference to the one obtained by the JMA researchers³³⁾, we set a fault plane whose strike, dip and rake angles are 202, 11, and 88 degrees, respectively, and assumed repeatedly various distributions of slip vectors in its dip direction on the plane. Here, the fault plane has a rectangular form of 500 km long and 200 km wide, composed of 100 small sub faults of rectangle in total. **Figure 12** shows a contour map of fault slips finally estimated by such a trial-and-error method as fitting the theoretical displacements with the observed ones at the GEONET sites in both horizontal and vertical components. The maximum slip on the fault plane inversely inferred by the method amounts to about 40 m giving upheaval of about 8 m. A comparison between the theoretically estimated displacements and the observed is shown in **Fig.13** for the horizontal and vertical components. **Figure 13** shows a good agreement of distributions between the theoretical and the observed displacements.

Figure 12 also presents a relation between the original dislocation of source fault and resultant deformation of the crust: a huge reverse-thrust fault of interplate earthquake like the 2011 Great East Japan Earthquake triggers enormous upheaval of the crust near the epicenter and at the same time subsidence or uplift of land depending on distances from the

source. Among these deformations of the crust, the upheaval in the epicenter area causes tsunami generation by lifting seawater while the subsidence at coastal-land places relatively far from the epicenter heightens the amplitude of traveling tsunami wave. This indicates theoretically that the GEONET data are useful to estimate how much tsunami arises in source and evolves in traveling process because they provide information regarding both origins of generation and amplification of tsunami. From this standpoint, it is expected in the near future that the GEONET data will be available on real-time basis to mitigate tsunami disasters.

5. ESTIMATE OF COSEISMIC STRAINS BY GEONET DATA AND DAMAGE ANALYSIS OF STRUCTURES

(1) Estimate of coseismic strains of grounds

The coseismic crustal deformations as shown in **Fig.3** finally result in the variation in ground strains that are the spatial differentials of displacements. In this paper, a strain of ground, which is numerically estimated by the spatial differential from the coseismic crustal displacements, is called “coseismic strain of ground.” This section discusses coseismic strains of ground and their relation with earthquake damage to civil engineering structures.

The importance of coseismic strains of ground has been long recognized relating with seismic behaviors of underground structures such as buried pipelines^{34), 35)}. As opposed to underground structures, conventional aboveground structures where the inertial effects are of primary interest had not been associated with coseismic strains of ground. The 1995 Kobe Earthquake provided a chance to reconsider such a situation. In response to the disastrous damage to various civil engineering structures by the earthquake, the Japan Society of Civil Engineers issued a proposal placing emphasis on the effects of coseismic strains of ground on civil engineering structures including aboveground ones³⁶⁾. The coseismic strains of ground, however, are more difficult to observe compared with other seismic parameters like acceleration³⁷⁾. Especially they have been hardly obtained during damage-causing earthquakes. Such a character of coseismic strains of ground makes it hard to discuss their effects on earthquake damage to civil engineering structures. At this point, the GEONET system might be useful to break through such dilemma. GEONET has provided variable data possible to obtain coseismic strains of ground due to damage-causing earthquakes that recently occurred in Japan. This section focuses on coseismic strains of ground estimated by

Fig.12 Theoretical displacements and inversely analyzed slip contour on the fault plane. Green thick line: contour of slip, Black rectangular line: assumed fault plane segment. Slip on the fault plane are assumed in the dip direction of the fault plane. The strike, dip and rake of the fault plane are assumed to be 202, 11, and 88 degrees, respectively. The fault plane is 500 km long and 200 km wide. Left: horizontal component of displacement, Right: vertical component of displacement.

Fig.13 Comparison between theoretical displacements and observed displacements by GEONET. Left: horizontal component of displacement, Right: vertical component of displacement.

the GEONET data to investigate their effects on earthquake damage to civil engineering systems found in the 2011 Great East Japan Earthquake⁵⁾ and

the 2008 Iwate-Miyagi Inland Earthquake³⁸⁾. The two earthquakes provided suitable data of coseismic displacements by the GEONET system as well as

extensive damage to civil engineering structures, enabling quantitative discussion over the relation between coseismic strains of ground and damage.

When the three-directional displacements are available at discrete points on the ground surface as shown in **Fig.3**, strains within the body surrounded by the points can be obtained by use of the spatial differential based on a theory of the plane strain condition. Here, we used a Finite Element Method (FEM) composed of triangular elements³⁹⁾. The FEM technique gives the normal strains ϵ_{NS} and ϵ_{EW} in respective directions of North-South, NS, and East-West, EW, shear strain γ_{NE} on the NS-EW plane and shear strains on the vertical plane using the three-directional displacements in the NS, EW, and vertical axes. From these strain components, we further estimated the maximum principal strain ϵ_{max} , minimum principal strain ϵ_{min} , maximum shear strain γ_{max} , volume strain ϵ_{volume} , and principal direction of strains on the NS-EW plane to represent the strain characteristics in each triangle element. Note here that the present FEM method provides strains smoothed over the length of some 20 km between each point of the triangular elements and gives no information on strains within more local areas of some 10 meters' level, which are considered to directly relate with damage of structures. Even such strains by the present method, however, are meaningful in vulnerability analyses to structures because their absolute maximum values have a general tendency to be proportional to the maximum of the local strains³⁵⁾. On the other hand, strains here are not dynamic but static because they are derived from permanent (static) displacements. It goes without saying that earthquake damage is generally due to dynamic effects; that is, dynamic strains oscillating during earthquakes in this case. Even so, the strains obtained by the present method might be a meaningful indicator of detectable damage to structures, because they have a proportional relation with the absolute peaks of dynamic strains³⁷⁾. This means that the present method can provide an index reliable enough to indirectly judge the vulnerability of structures to seismic forces.

We used the Delaunay triangulation method⁴⁰⁾ to form the net of triangle elements from the observation points of GEONET. **Figure 14** shows a triangle net system obtained by the method for the GEONET observation points. The center of the triangle was used to represent the estimated strains in each element.

Figure 15 shows the distributions for the estimated absolute values of the maximum principal strain, which is tensile strain, and maximum shear strain due to the 2011 Great East Japan Earthquake.

Fig.14 Triangle net system obtained by the Delaunay triangulation method for the GEONET observation points.

The directions of the principal strain axis are also plotted in **Fig.15**. In **Fig.15**, each strain is expressed in a logarithmic scale using a color image together with contour lines. Both maximum principal strain and maximum shear strain have a similar distribution with a slight difference in absolute values. Their absolute values amount to a level of some 0.0001 and show local peaks mainly in coastal areas near the epicenter. At the same time, their principal axes have a polarized direction almost toward the epicentral area reflecting the faulting mechanism of the earthquake source. On the other hand, **Fig.16** shows the distribution of the absolute values for the shear strain on the vertical plane that was estimated by spatially differentiating vertical displacements along the EW axis. The shear strain on the vertical plane has smaller values showing a distribution different from the maximum principal strain and maximum shear strain on the horizontal plane in **Fig.15**. Its distribution trend is related closely with the one of vertical displacements, whereas the strains on the horizontal plane have a close relation with horizontal displacements.

In addition to the 2011 Great East Japan Earthquake, another disastrous earthquake that recently occurred in Japan, the 2008 Iwate Miyagi Inland Earthquake³⁸⁾, is investigated here to complement discussions about coseismic strains of ground. The earthquake occurred in a land area with a magnitude of 7.2, triggering serious damage to various structures. GEONET succeeded in observing coseismic

Fig.15 Distributions of estimated coseismic strains for the 2011 Great East Japan Earthquake. Left: maximum principal strain, Right: maximum shear strain.

crustal deformations in the epicentral area for the earthquake. **Figure 17** shows the coseismic crustal deformations obtained by GEONET during the earthquake. This earthquake occurred in land with a source mechanism of reverse thrust fault. Reflecting such a mechanism, the coseismic displacements on the horizontal plane emerged reversely pointing to almost west and east, respectively, in each opposite side across the epicenter and the vertical displacements showed remarkable upheaval in the epicentral area, as well as subsidence in areas far from the epicenter. The coseismic strains of ground were obtained from the crustal deformations similarly to the case of the 2011 Great East Japan Earthquake, as shown in **Fig.18**. The maximum principal strain and maximum shear strain in **Fig.18** show a distribution trend slightly different from each other. Their absolute values are also rather larger than those induced by the 2011 Great East Japan Earthquake in **Fig.15**, concentrating on the epicentral area. This means that an inland earthquake with short epicentral distance can trigger larger strains in areas near its source.

(2) Damage to civil engineering structures

The 2011 Great East Japan Earthquake caused tremendous damage extensively in the northeast district of Japan; thus, many research teams investigated damage related with various kinds of structures and compiled a great number of reconnaissance reports. Especially the Joint Reconnaissance

Fig.16 Distribution of the absolute value for the shear strain on the vertical plane that was estimated by spatially differentiating vertical displacements along the EW axis.

Committee organized by the Tohoku branches of seven academic societies issued a detailed report on damage to civil engineering systems consisting

mainly of bridges and their related substructures⁴¹⁾. The damage levels to structures taken up in the report were relatively high so that the relevant prefectural offices adopted some restoration or repair works. The report by the committee includes numerical positions of latitude and longitude for the damage sites in the three prefectures of Iwate, Miyagi, and Fukushima, based on an elaborate fieldwork. See the committee report⁴¹⁾ for details. **Figure 19** shows a map of the damage sites cited in the report together with the altitude of ground. **Figure 19** reveals that the damage sites are almost linearly distributed along the source fault of the earthquake and tend to scatter in alluvial planes with low altitude.

For the 2008 Iwate-Miyagi Inland Earthquake, on the other hand, a joint reconnaissance committee also conducted investigations of damage sites for civil engineering structures⁴²⁾. The damage was mainly caused by ground failure because the earthquake occurred in a mountainous area and the number of damage sites had a great scope ranging from minor to severe levels. The committee compiled a detailed report of these damage sites based on elaborately organized fieldworks. **Figure 20** shows a map of these damage sites cited in the committee report with the altitude of ground. **Figure 20** illustrates that the damage sites scatter around the epicenter showing a tendency to concentrate on the southern area rather than on the northern area

Fig.17 Coseismic crustal deformations obtained by GEONET during the 2008 Iwate Miyagi Inland Earthquake. Left: horizontal component, Right: vertical component.

Fig.18 Distributions of estimated coseismic strains for the 2008 Iwate-Miyagi Inland Earthquake. Left: maximum principal strain, Right: maximum shear strain.

against the epicenter.

In order to investigate the scattering characteristics of the damage sites due to both earthquakes, they are compared with the distributions of coseismic strains of ground by overlapping their respective maps. **Figure 21** shows such comparisons for the 2011 Great East Japan Earthquake while **Fig.22** for the 2008 Iwate-Miyagi Inland Earthquake. In both figures, the distributions of coseismic strains of ground are expressed by a color image with contour lines. **Figure 21** compares the damage sites with the maximum shear strain on the horizontal plane as well as the shear strain along the EW axis on the vertical plane for the 2011 Great East Japan Earthquake. **Figure 21** demonstrates that both strain distributions explain relatively well the scattering trend of the damage sites, though the shear strains on the vertical plane agree with the distribution of damage sites better than the shear strains on the horizontal plane. **Figure 21** also clarifies that the damage sites are located almost within the areas having maximum horizontal shear strains of over $10^{-4.5}$ (some 0.00003), suggesting a failure limit of civil engineering structures in terms of coseismic strains of ground. Meanwhile, **Fig.22** illustrates the comparisons between the damage sites and both of the maximum principal strain and maximum shear strain on the horizontal plane for the 2008 Iwate-Miyagi Inland Earthquake. It is clear in **Fig.22** that there is a good agreement in distributions between the maximum shear strain and damage sites. **Figure 22** also shows that the damage sites scatter almost within the areas of over $10^{-4.5}$ (some 0.00003) maximum horizontal shear strain, consistent with the case of the 2011 Great East Japan Earthquake. Note here that the present value of the strains never means a limit value physically defined from the standpoint of fracture mechanics. It is an indicator to indirectly estimate the vulnerability of structures to seismic forces as described previously.

(3) Statistical analyses of damage and strains

In order to investigate the statistics of the relation between damage to structures and coseismic strains of ground, a histogram analysis was made for both earthquakes. **Figure 23** shows the analyzed histograms for both earthquakes, illustrating correlations between the number of damage sites and values of maximum shear strain. It is seen in **Fig.23** that there is a generally proportional trend between the number of damage and the values of maximum shear strain. A threshold value of maximum shear strain is also found in **Fig.23** to judge where civil engineering structures are vulnerable; most of structures are possibly vulnerable at places where the peak

Fig.19 Distribution of damage sites of civil engineering structures due to the 2011 Great East Japan Earthquake.

Fig.20 Distribution of damage sites of civil engineering structures due to the 2008 Iwate-Miyagi Inland Earthquake.

shear strain exceed some $10^{-4.7}$ (0.00002) $\sim 10^{-4.5}$ (0.00003). **Figure 23** implies that coseismic strains of ground play a role in damaging civil engineering systems, while other seismic parameters like seismic intensity connected closely with inertia force might have a similar role. Here, we compare the difference in their roles for deciding damage to

Fig.21 Comparison between the damage sites of civil engineering structures and coseismic strains of ground due to the 2011 Great East Japan Earthquake.

Left: Comparison of the damage sites with maximum shear strain.

Right: Comparison of the damage sites with shear strain on the vertical plane along EW axis.

Fig.22 Comparison between the damage sites of civil engineering structures and coseismic strains of ground due to the 2008 Iwate-Miyagi Inland Earthquake.

Left: Comparison of the damage sites with maximum principal strain.

Right: Comparison of the damage sites with maximum shear strain.

civil engineering structures. **Figure 24** shows a comparison between the distributions of seismic intensity and damage sites which were already plotted in **Fig.19** for the 2011 Great East Japan Earthquake. Similar comparison is also shown in **Fig.25**

for the 2008 Iwate-Miyagi Inland Earthquake. **Figure 24** indicates that seismic intensity correlates with damage site to such a degree as coseismic strains of ground for the 2011 Great East Japan Earthquake. For the 2008 Iwate-Miyagi Inland

Fig.23 Histograms of damage sites by maximum shear strain.
Left: Histogram for the 2008 Iwate-Miyagi Inland Earthquake.
Right: Histogram for the 2011 Great East Japan Earthquake.

Fig.24 Comparison between the damage sites of civil engineering structures and seismic intensity due to the 2011 Great East Japan Earthquake.

Fig.25 Comparison between the damage sites of civil engineering structures and seismic intensity due to the 2008 Iwate-Miyagi Inland Earthquake.

Earthquake in **Fig.25**, however, seismic intensity has less correlation with damage site compared to coseismic strains of ground. This suggests that coseismic strains of ground exert greater influence on

civil engineering systems than seismic intensity does, as expected from an understanding that civil engineering structures having long or large configuration in space are prone to spatially-varying parameters like coseismic strains of ground.

The above suggestion is based on two limited experiences of earthquakes; thus, we need further studies to deepen and generalize the present result in future damaging earthquakes. In addition, it is necessary to analyze the effects of coseismic strains of ground on damage to structures using a more accurate method of classifying the level of damage de-

pendently on the types of structures.

6. CONCLUDING REMARKS

This paper presents the potential and capability of GEONET data to enhance countermeasures to earthquake disasters. Because the GEONET system provides spatiotemporal information on crustal deformations due to seismic forces, it can offer applications in various fields from both points of view of space and time. We offer three applications: (1) the application to earthquake prediction; (2) the application to tsunami early warning system; and (3) the application to damage analysis of civil engineering systems. The ideas of these applications were all learned from the disastrous experiences due to the 2011 Great East Japan Earthquake. The earthquake triggered historically the worst disaster to Japanese society, especially to people living in the northeast part of Japan. The authors, who have been working as a group of specialists of earthquake-related research in the disastrous area, could not fulfill their original responsibility to mitigate the disaster. This unfortunate experience led us to come up with ideas using the GEONET system applicable to truly reduce the number of victims during huge interplate earthquakes. The main results of the paper are summarized as follows:

(1) Possibly precursory crustal movements appeared in the GEONET data before the 2011 Great East Japan Earthquake with different time-scales: several months (medium term), about three days to one week (short term), and a few hours (imminent). Among them, short-term movements might be sufficiently convincing as precursors. The reason that we regard these as the precursor to the earthquake is based on the following facts: 1) abnormal and unusual variations appeared showing an explicitly different trend from the past; 2) such abnormality was simultaneously detected at many sites; and 3) such abnormal variations tended to increase day by day, especially in variations in the azimuth of displacements. Moreover, the precursor detected for the earthquake on three days earlier than the event was interestingly consistent, in its time scale, with the abnormal phenomena of the crust experienced for the 1944 Tonankai Earthquake (Mogi 1985¹⁸). Although these behaviors of the crust prior to the 2011 Great East Japan Earthquake were detected by GEONET based on retroactive analyses, they suggest a strong potential and applicability of the GEONET data to earthquake prediction on real-time basis of their data treatment.

(2) A great deal of subsidence of land were detected by GEONET at sites along the Pacific Coast

in northeast Japan during the 2011 Great East Japan Earthquake. This subsidence of land had a close correlation with the height of the tsunami propagating in the areas, indicating they had a role in amplifying the traveling tsunami height. In addition, GEONET inversely provides information on crustal deformations, especially upheaval value of the crust, near the seismic source. For the 2011 Great East Japan Earthquake, GEONET inversely estimates crustal upheavals of about 8 m from its observed data of crustal deformations on land. This means that GEONET provides both information on how much tsunami arises in source and how much evolves in the traveling process. It is expected that GEONET data on real-time basis will be utilized to predict tsunami height at a site after interplate earthquakes.

(3) The 2011 Great East Japan Earthquake triggered great deformations of the crust to the Japanese islands, amounting to some 5 m and 1m, respectively, on the horizontal and vertical planes in areas near the epicenter. These enormous deformations caused feasible effects of coseismic strains of ground on civil engineering systems. The damage sites of civil engineering systems have a good correlation with the value of induced coseismic strains of ground. Such a good correlation was confirmed not only for the 2011 Great East Japan Earthquake but also for the 2008 Iwate-Miyagi Inland Earthquake. Most civil engineering structures are possibly vulnerable at places where the peak shear strain exceed some $10^{-4.7}(0.00002) \sim 10^{-4.5}(0.00003)$. This indicates that GEONET data are applicable for estimating damage sites of civil engineering system immediately after an earthquake by analyzing coseismic strains of ground on real-time basis.

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