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Original article

Estimation of the Crustal Deformation Caused by Earthquake and Its Use in Updating Published Coordinates of Geodetic Control Points - A Case Study of the 2011 Tohoku Earthquake's Impact in South Korea

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Abstract

The Tohoku Earthquake, which hit Japan on March 11, 2011, was a massive magnitude 9.0 earthquake, with the earthquake itself causing damage and the resulting tsunami additionally causing enormous material and human damage. The crustal deformation at that time reached a maximum of 5.24 m in Japan, Neighboring countries South Korea and China as well as the Southeast Asian region also witnessed crustal deformation ranging from a few centimeters to a few meters. The detailed analysis in this study based on data from 72 of the sites in South Korea where GNSS CORS was installed showed that South Korea underwent heterogeneous crustal deformation from the Tohoku earthquake, with a maximum of 55.5 mm, a minimum of 9.2 mm, and an average of 22.42 mm. A crustal deformation model was developed, applied, and evaluated for accuracy in this study for a prompt revision of the survey results of the control points that were changed by the crustal deformation. The survey results were revised by applying a crustal deformation model to the 1,195 unified control points installed in South Korea prior to the Tohoku earthquake. The comparison of these 1,195 points with their new survey results showed that the RMSE decreased from 14.1 to 3.4 mm and that the maximum result difference declined from 39 to 10 mm. Revision of the survey results of the control points using the crustal deformation model is deemed very useful considering that the accuracy of the survey results of the unified control points in South Korea is 3 cm.

Keywords : 2011 Tohoku Earthquake, Crustal Deformation, Unified Control Points

1. Introduction

The 2011 earthquake off the Pacific coast of Tohoku (hereinafter, “Tohoku Earthquake”) was a magnitude 9.0 earthquake that occurred at 70 km off the coast of Sanriku, Japan, at a depth of 30 km, at 14:46 KST (05:46 UTC) on March 11, 2011. It was not only the strongest earthquake that ever occurred in Japan but was also the fourth most powerful earthquake that ever occurred in the world after 1900 (USGS, 2011; NPA, 2015). While massive earthquakes like the Tohoku Earthquake lead to instantaneous and direct damage such as loss of human lives and destruction of houses, they also cause long-term damage such as ground subsidence, uplift, crustal deformation, and the shifting of the Earth's rotation axis, which can impact the planet's environment and ecosystem. Actually, the Tohoku Earthquake moved towards the northeastern area of Japan at a maximum distance of 5.24 m and an average distance of 2.4 m horizontally, and a maximum distance of 0.699 m vertically. As a result, the whole of Japan suffered heterogeneous crustal deformation and ground subsidence, and this subsidence of the eastern coast caused a change in the coastline (ARIA, 2011). Calculations also show that the Japan quake could have shifted the position of the Earth's figure axis (the axis about

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which the Earth's mass is balanced) by about 17 cm towards 133 degrees east longitude, causing the Earth's rotation period to become shorter and the length of a day to be reduced by 0.0000018 seconds (NASA, 2011).

As aforementioned, an earthquake can have a tremendous impact and can cause massive damage in terms of its targets and ranges, and a large-scale earthquake can have a worldwide impact. The crustal deformation caused by the Tohoku Earthquake reached not only Japan but also the Korean Peninsula, China, Russia, and the Southeast Asian region, which were close to its epicenter. South Korea suffered a crustal deformation of about 2 cm (SUWN), China 0.3 cm (WUHN), and Russia 1 cm (IRKT), based on the IGS (International GNSS Service) global stations (Gu and Wang, 2011).

The crustal deformation that occurs due to a massive earthquake like the Tohoku Earthquake is huge and heterogeneous. Basic and public surveying in South Korea determine the coordinates of unknown points by performing network adjustments, with the survey results of the control points being fixed points after the relative distances from the control points, such as the GNSS CORS (Continuously Operation Reference Stations) or the unified control points, to the unknown points are measured. Therefore, the survey results of the control points (i.e., the precision of the baseline distance between the control points) greatly affect the quality of the survey results. When the baseline distance between the control points is changed by heterogeneous crustal deformation, network adjustment after the survey made without considering this change may lead to low-quality survey results because the change in the baseline distance will remain a survey error (Leick, 2004; Cho *et al*., 2011).

Japan, where a 5m maximum crustal deformation was observed after the Tohoku Earthquake, completely stopped providing the survey results of VLBI, GEONET (GPS observation network), triangulation points, and benchmarks on March 14, 2011, three days after the earthquake. It considered the stabilization time of post-seismic crustal deformation and started providing revisions of the survey results of GEONET on May 31, 2011, and those of the triangulation points and benchmarks on Oct. 31, 2011 (Hiyama *et al*., 2011).

Japan, which is often hit by earthquakes, conducted numerous revisions of survey results of the control points associated with crustal deformations before the Tohoku Earthquake. To efficiently revise the survey results of many control points within a short period, a crustal deformation model was applied. PatchJGD, developed by Geospatial Information Authority of Japan, is a program designed for revising the survey results of the control points through a crustal deformation model. It can revise not only the survey control points but also diverse spatial information (Tanaka *et al*., 2007).

Cho *et al*. (2011) calculated the crustal deformation of the Korean Peninsula on ordinary days without earthquakes, and the relative baseline distances between the GNSS CORS, through a precise analysis of the 30-month data from the 45 GNSS CORS in and around South Korea. They suggested the use of a crustal deformation model to revise the GNSS CORS survey results every decade, and to improve the DGPS accuracy.

As the survey results of control points are the base data for all national spatial information, any change in locations bigger than the stipulated accuracy must be dealt with by providing new survey results within the shortest time. GNSS CORS can calculate the most recent survey results instantly by using permanent data, but unified control points and triangulation points cannot allow instant calculation, and their calculation entails much time and expense as it requires new surveying.

The crustal deformation in South Korea due to the Tohoku Earthquake was calculated in this study through a precise analysis of the GNSS CORS data. An experiment was conducted using a revision method through crustal deformation modeling as a way of revising the survey results of unified control points within a short time. The revised survey results were compared with the actual survey results to evaluate accuracy and usability.

2. Analysis of Crustal Deformation Using GNSS CORS

2.1 Strategy of GNSS CORS data processing

The precise survey results of the GNSS CORS in South Korea before and after the Tohoku Earthquake were

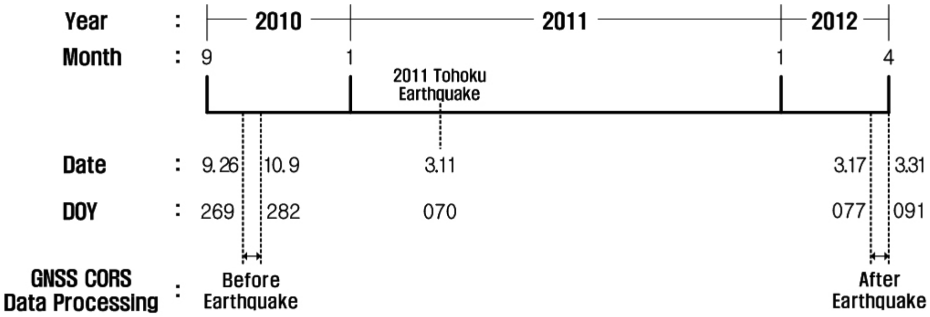

Fig. 1. GNSS CORS data processing period for calculating the crustal deformation caused by the Tohoku Earthquake

Table 1. Status of the GNSS CORS in South Korea for crustal deformation analysis (as of Mar. 11, 2011)

Management agency (No. of CORS)	**NGII (44)**			**LX (2)**	**NMPNT (26)**	
Station Name	BOEN	INJE	SEOS	ANSG	ANHN	MOOJ
	CHCN	JAHG	SNJU	CHWN	CCHJ	PALM
	CHEN	JEJU	SONC		CCHN	PYCH
	CHJU	JINJ	SOUL		DANG	SEJU
	CHLW	JUNG	SUWN		DOKD	SEOI
	CHNG	JUNJ	TABK		EOCH	SOCH
	CHSG	KANR	TEGN		GASA	SOHE
	CHYG	KIMC	WNJU		GEOM	SORI
	CNJU	KUNW	WOLS		HGDO	ULLE
	DOND	KWNJ	WULJ		HOMI	YNDO
	GOCH	MUJU	YANP		JEOJ	YNJU
	GSAN	NAMW	YECH		JUKB	
	HADG	NONS	YONK		JUMN	
	HONC	PAJU	YOWL		MARA	
	INCH	PUSN			MLDO	

compared in this study to analyze the crustal deformation in South Korea caused by the quake. GAMIT/GLOBK, a program developed by MIT for GNSS precise baseline analysis and network adjustment, was used for GNSS CORS data processing. The survey results of the GNSS CORS in South Korea are being calculated using GNSS data precise analysis programs such as GAMIT/GLBOK, GIPSY-OASIS II, and BERNESE. Each of these precise analysis programs, however, can yield different results when a different analysis strategy (IGS global network, reference frame, stabilization site, data acquisition period, etc.) is applied. Therefore, the GNSS CORS locations before the quake were processed by applying the same baseline analysis and network adjustment strategy before and after the quake, without using the survey results announced by the National Geographic Information Institute (NGII), to calculate new locations and to remove the systematic error during the calculation.

The crustal deformation that accompanies an earthquake can be divided into pre-, co-, and post-seismic crustal deformation based on the timing. Most earthquakes cause fine and unstable crustal deformation before and after their occurrence. The crustal deformation generated during an earthquake can be partly recovered over a few days or months (Sato *et al*., 2011). This is due to the restoring force based on the elastic rebound theory of the ground or the continuous movement of the unstable ground. Therefore, the GNSS CORS locations must be calculated at sufficiently stabilized periods of the crustal deformation both before and after an earthquake. The sufficiently stabilized periods selected in this study were 6 months (2010.740-2010.773) before the Tohoku Earthquake (2011.192) and 12 months (2012.211-2012.249) after the quake. The data from the IGS stations and GNSS CORS in South Korea for 14 days in each period were processed and averaged to obtain the location survey results before and after the quake.

As of March 11, 2011, when the Tohoku Earthquake occurred, NGII provided the GNSS CORS data of a total of 72 stations. Two of these stations were GNSS CORS managed by Korea Land and Geospatial Informatix Corporation (LX), while 26 stations were managed by the National Maritime PNT Office (NMPNT). A precise analysis of the 72 stations was performed in this study after checking if there was any GNSS CORS that had changed its survey results due to relocation, antenna replacement, etc. during the data processing period (Oct. 2010-Mar. 2012), for crustal deformation calculation. The GNSS CORS data processing period and locations are shown in Fig. 1 and Table 1, respectively.

2.2 GNSS CORS data processing

GAMIT/GLOBK was used in GNSS CORS data processing, and 「combining the global and local quasi-observation solutions」 (Cho, 2006) was applied as a baseline and network adjustment processing strategy for the analysis of the crustal deformation in South Korea caused by the Tohoku Earthquake. Baseline processing was performed by connecting 72 GNSS CORS in South Korea (including SUWN) and 9 IGS stations around South Korea (including 5 core site stations and DAEJ). Subsequently the global and local quasi-observation data of 284 global IGS stations were combined. The GNSS CORS in South Korea and the IGS stations around South Korea that were used for the baseline analysis are shown in Fig. 2 and 3, respectively, and in Table 1 and 2.

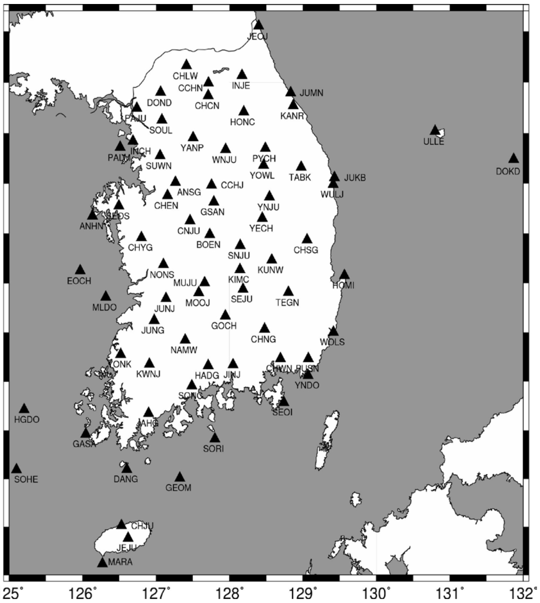

Fig. 2. GNSS CORS in South Korea used for the analysis of the crustal deformation caused by the Tohoku Earthquake

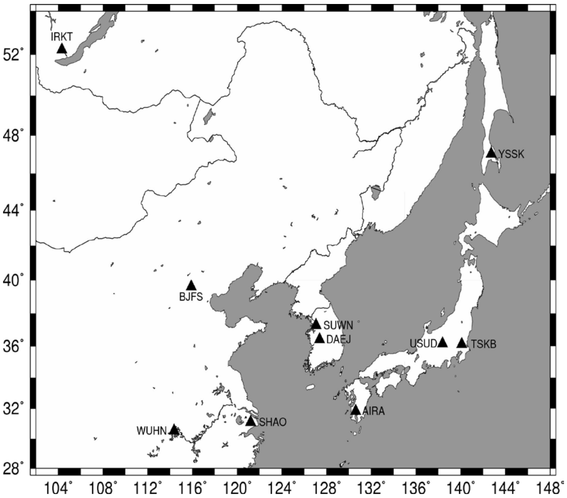

Fig. 3. IGS stations in East Asia used for the analysis of the crustal deformation caused by the Tohoku Earthquake

Table 2. IGS stations in East Asia used for the analysis of the crustal deformation caused by the Tohoku Earthquake

Nation	Station Name	IGS Core Site
Korea	SUWN	
	DAEJ	
Japan	AIRA	
	USUD	
	TSKB	○
Chinese	WUHN	○
	BJFS	○
	SHAO	
Russia	IRKT	○
	YSSK	○

2.3 Quality of GNSS baselines processing and network adjustment

The quality of the GNSS baseline processing can be assessed using repeatability of the independent baseline components (Duong *et al*., 2005; Herring *et al*., 2015a). The mean WRMS (weighted RMS) of the daily baseline processing results by bias-free and bias-fixed solutions in this study is shown in Table 3. The bias-fixed solution that had a small average WRMS between the two solutions was used in this study.

Fig. 4 shows the baseline component repeatabilities vs. the baseline length. The maximum baseline length was about 3,200 km, the maximum WRMS of the north component in the bias-fixed solution was 4.5 mm, and the maximum WRMS of the east component was 4.6 mm. The average WRMS for the entire baseline was 1.4 mm.

Table 3. Mean WRMS of the baselines from the daily solution

Solution type	Mean WRMS (mm)	
	North	East
bias-free	0.9	1.6
bias-fixed	0.9	1.1

The quality of the global network adjustment of the GNSS CORS in South Korea and the IGS global stations can be evaluated based on the reference variance ($\hat{\sigma}_0^2$), with the value of 1 as excellent (Herring *et al*., 2015b). As the reference variance that was obtained in this study by combining the network adjustment of a local network and that of an IGS network was 0.995, the result of the network adjustment was considered excellent.

2.4 Crustal deformation in South Korea caused by the Tohoku Earthquake

Based on the results of the GNSS data processing, the

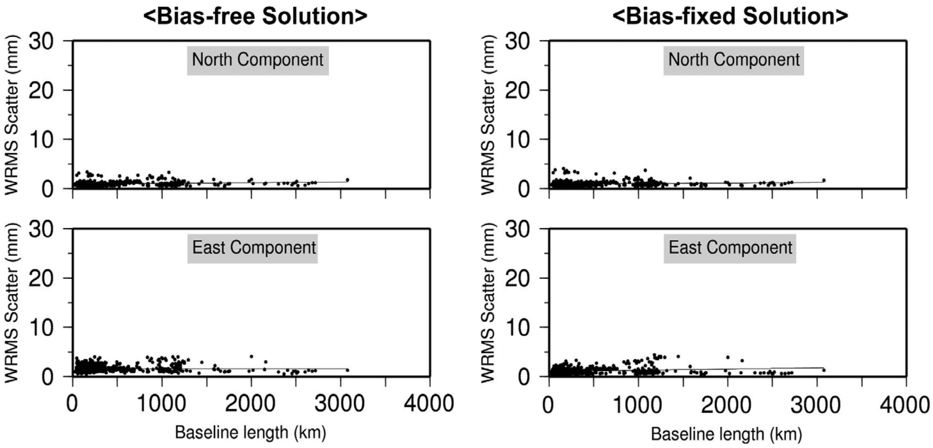

Fig. 4. Baseline component repeatabilities vs. baseline length (the thin line represents the best-fitting line)

horizontal displacements of the IGS stations in East Asia caused by the Tohoku Earthquake are shown in Fig. 5 and Table 4. The horizontal displacements of the GNSS CORS in South Korea are shown in Fig. 6 and Table 5. The displacement of the TSKB station in Japan was the biggest (60.3 cm) among the targeted IGS stations. The displacement of the SUWN station in South Korea was about 2.2 cm, and that of the WUHB station in the southeastern part of China was 0.7 cm (Fig. 5). Among the GNSS CORS in South Korea, the DOKD station, which is closest to the epicenter of the quake, had the highest displacement (5.6 cm), while the MARA station, which is farthest from the epicenter, had the lowest displacement (0.9 m).

The analysis results of the vectors of the crustal deformation in South Korea and East Asia caused by the Tohoku Earthquake showed that the direction of the crustal deformation was towards the epicenter of the quake located in the coast of Sanriku in eastern Japan, The magnitude of the crustal deformation tended to decrease with the distance from the epicenter.

Table 4. Horizontal displacements of the IGS stations in East Asia caused by the Tohoku Earthquake

Station	D_N (mm)	D_E (mm)	D_S (mm)*
AIRA	3.0	17.0	17.3
BJFS	1.0	12.0	12.0
DAEJ	2.0	29.0	29.1
IRKT	5.0	13.0	13.9
SHAO	2.0	12.0	12.2
SUWN	1.0	22.0	22.0
TSKB	34.0	602.0	603.0
USUD	48.0	239.0	243.8
WUHN	-1.0	7.0	7.1
YSSK	-7.0	7.0	9.9

$* \; D_S = \sqrt{(D_N^2 + D_E^2)}$

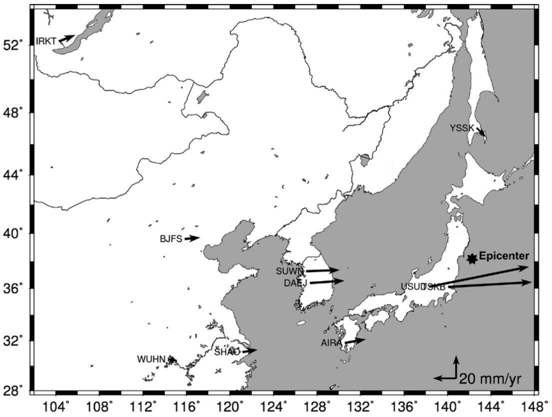

Fig. 5. Horizontal displacements of the IGS stations in East Asia caused by the Tohoku Earthquake

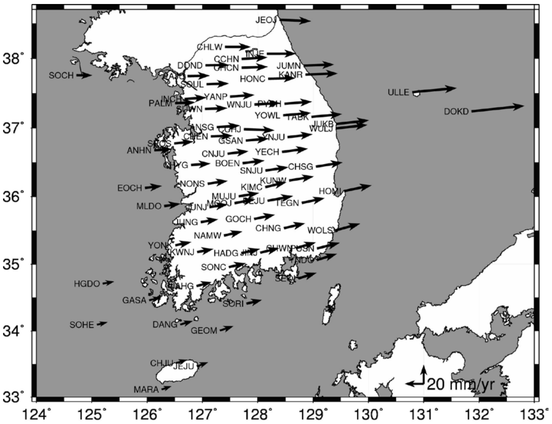

Fig. 6. Horizontal displacements of the GNSS CORS in South Korea caused by the Tohoku Earthquake

Table 5. Horizontal displacements of the GNSS CORS in South Korea caused by the Tohoku Earthquake

Staion	D_N(mm)	D_E(mm)	D_S(mm)	Station	D_N(mm)	D_E(mm)	D_S(mm)	Station	D_N(mm)	D_E(mm)	D_S(mm)
ANHN	1.2	17.5	17.6	HOMI	5.9	27.9	28.6	PUSN	5.7	22.6	23.3
ANSG	1.6	23.1	23.2	HONC	0.7	27.7	27.7	PYCH	2.1	27.7	27.8
BOEN	2.7	21.9	22.1	INCH	1.5	21.7	21.7	SEJU	4.8	25.6	26.0
CCHJ	-1.2	30.9	30.9	INJE	0.2	29.9	29.9	SEOI	5.6	17.8	18.7
CCHN	1.8	26.1	26.2	JAHG	3.9	14.5	15.0	SEOS	1.9	18.9	19.0
CHCN	1.0	26.6	26.7	JEJU	3.7	10.3	11.0	SNJU	3.4	22.9	23.1
CHEN	0.7	21.7	21.7	JEOJ	-1.4	32.1	32.1	SOCH	0.0	15.1	15.1
CHJU	3.2	10.3	10.7	JINJ	4.4	18.7	19.2	SOHE	2.4	9.9	10.2
CHLW	0.0	26.0	26.0	JUKB	3.8	33.0	33.2	SONC	3.8	16.4	16.8
CHNG	4.9	21.2	21.8	JUMN	1.1	31.0	31.0	SORI	3.6	14.7	15.1
CHSG	4.2	26.7	27.0	JUNG	2.8	17.0	17.2	SOUL	0.8	22.4	22.4
CHWN	5.9	20.1	20.9	JUNJ	2.7	17.7	17.9	SUWN	0.9	22.4	22.4
CHYG	1.5	19.1	19.1	KANR	1.1	32.9	32.9	TABK	2.9	30.9	31.0
CNJU	2.5	20.9	21.0	KIMC	5.1	21.2	21.8	TEGN	4.8	22.9	23.4
DANG	3.2	11.8	12.2	KUNW	4.2	24.8	25.1	ULLE	4.3	46.2	46.4
DOKD	5.9	55.4	55.7	KWNJ	3.1	15.7	16.0	WNJU	1.5	25.9	25.9
DOND	0.4	23.7	23.7	MARA	2.9	8.7	9.2	WOLS	6.7	24.5	25.4
EOCH	1.9	16.1	16.2	MLDO	2.3	15.7	15.9	WULJ	3.7	32.3	32.5
GASA	2.8	11.4	11.7	MOOJ	3.8	20.5	20.8	YANP	1.7	24.6	24.6
GEOM	4.3	12.8	13.5	MUJU	3.3	20.2	20.4	YECH	3.3	26.1	26.3
GOCH	4.3	20.7	21.1	NAMW	4.0	17.9	18.3	YNDO	6.2	20.0	20.9
GSAN	1.9	23.0	23.1	NONS	2.9	19.9	20.1	YNJU	2.9	25.1	25.2
HADG	4.2	18.3	18.8	PAJU	0.5	22.0	22.0	YONK	3.1	15.4	15.7
HGDO	2.0	10.6	10.7	PALM	0.8	19.9	20.0	YOWL	2.4	28.1	28.2

3. Update of the Survey Results of the Unified Control Points Using the Crustal Deformation Model

3.1 Installation status of the unified control points in South Korea

A unified control point is the control point that unifies the triangulation point (the control point of a horizontal survey) and the benchmark (the control point of a vertical survey). It is the name of the control points that are being installed in South Korea. NGII started installing unified control points in 2008, and it targets to have installed about 7,000 by 2018. The installation locations and quantities of unified control points by year are shown in Fig. 7.

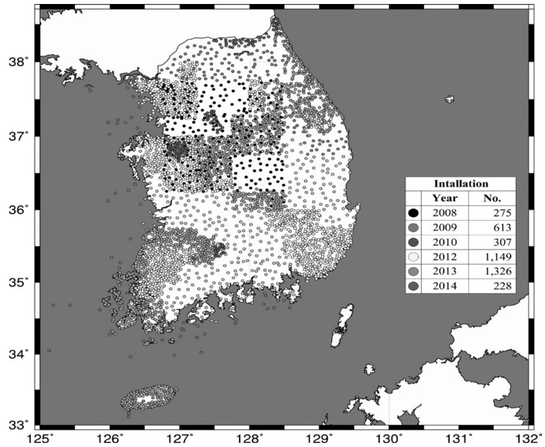

Fig. 7. Installation locations and quantities of unified control points in South Korea by year

3.2 Update strategy of the survey results of the unified control points

NGII surveyed and completed the public announcement of the results of the 1,195 unified control points installed between 2008 and 2010 in Dec. 2010. No unified control point was installed in 2011, the year the Tohoku Earthquake occurred, and the installation restarted in 2012. The Tohoku Earthquake generated heterogeneous crustal deformation in South Korea, as seen in Fig. 6 and Table 5, and it affected the locations of the points installed before the quake.

As the heterogeneous crustal deformation led to changes in the relative distances between the control points, any survey using these points without considering such changes will obtain erroneous results (Cho *et al*., 2011). Therefore, if the crustal deformation caused by a quake exceeded the required survey quality, the survey results of the control points must be updated.

In the case of the GNSS CORS, the survey results after a quake can be updated within a comparably short time so stations are constantly acquiring data before and after a quake. In the case of the unified control points, however, update of their survey results after a quake entails much time and expense as new surveys need to be conducted. Futhermore, unified control points cannot be used before the update of survey results. A crustal deformation model for GNSS CORS data processing was applied in this study as a way of updating the survey results of the unified control points displaced by an earthquake within a short time. Also, the accuracy of the survey results updated using the crustal deformation model was evaluated using the survey data obtained at some of the unified control points after a quake.

The survey results of the 1,195 unified control points installed before the Tohoku Earthquake were updated using the crustal deformation model, and the survey results of the points installed after the quake were updated using the surveyed data (Fig. 8). NGII performed new GNSS surveys after the Tohoku Earthquake on 119 common points, which were among the unified control points installed before the quake. These data were used to evaluate the accuracy of the survey results update using the crustal deformation model.

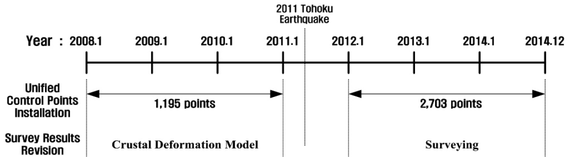

Fig. 8. Update strategy of the survey results of the unified control points

3.3 Crustal deformation model for the Tohoku Earthquake

The crustal deformation model for updating the survey results of the unified control points was used for calculating the GNSS CORS dislocations in South Korea presented in Table 5. As the results of the detailed analysis of the GNSS CORS data show, the direction of the crustal deformation in South Korea caused by the Tohoku Earthquake was towards the epicenter of the quake, and the magnitude of the crustal deformation tended to decrease linearly with the distance from the epicenter. The crustal deformation model was obtained by applying the linear model equation used by Hiyama *et al*. (2011) for the revision of the survey results of the control points in Japan after the Tohoku Earthquake. The crustal deformation according to the GNSS CORS location can be expressed by the following equation:

$$a\phi_C + b\lambda_C = \Delta_{\phi_C}, \; c\phi_C + d\lambda_C = \Delta_{\lambda_C} \tag{1}$$

where ϕ_C, λ_C : latitude and longitude of the GNSS CORS
Δ_{ϕ_C}, Δ_{λ} : latitude and longitude displacements of the GNSS CORS

The equation for obtaining the correction parameters *a* and *b* is expressed by applying the least square method to equation (1) (Cho *et al*., 2004) as follows:

$$\begin{bmatrix} a \\ b \end{bmatrix} = A \begin{bmatrix} \sum_i \lambda_{C_i} & -\sum_i \phi_{C_i}\lambda_{C_i} \\ -\sum_i \phi_{C_i}\lambda_{C_i} & \sum_i \phi_{C_i} \end{bmatrix} \begin{bmatrix} \sum_i \phi_{C_i}\Delta_{\phi_{C_i}} \\ \sum_i \lambda_{C_i}\Delta_{\phi_{C_i}} \end{bmatrix} \tag{2}$$

where $A = \dfrac{1}{\sum_i \phi_{C_i}^2 \sum_i \lambda_{C_i}^2 - (\sum_i \phi_{C_i}\lambda_{C_i})^2}$

Correction parameters *c* and *d* can be calculated in the same manner using longitudinal displacement.

The crustal deformation that occurred at a certain point in South Korea can be expressed as equation (3) by applying the correction parameters obtained in equation (2) and the weighting on the Earth's spherical distance.

$$\Delta_{\phi_j} = \frac{\sum_i (\Delta_{\phi_{C_i}} / D_{ij}^2)}{\sum_i (1/D_{ij}^2)} + a\phi_{C_j} + b\lambda_{C_j} + \Delta_{\phi_{C_i}}$$

$$\Delta_{\lambda_j} = \frac{\sum_i (\Delta_{\lambda_{C_i}} / D_{ij}^2)}{\sum_i (1/D_{ij}^2)} + c\phi_{C_j} + d\lambda_{C_j} + \Delta_{\lambda_{C_i}} \qquad (3)$$

where $D_{ij} = \arccos(x_i x_j + y_i y_j + z_i z_j)$

$$x = \cos\phi_C \cos\lambda_C$$
$$y = \cos\phi_C \sin\lambda_C$$
$$z = \sin\phi_C$$

The GNSS CORS displacements in South Korea and the correction parameters *a*, *b*, *c* and *d* calculated from equation (2) are listed in Table 6.

Table 6. Crustal deformation model parameters

parameter	value
a	-6.4×10^{-9}
b	2.0×10^{-9}
c	2.22×10^{-8}
d	-5.1×10^{-9}

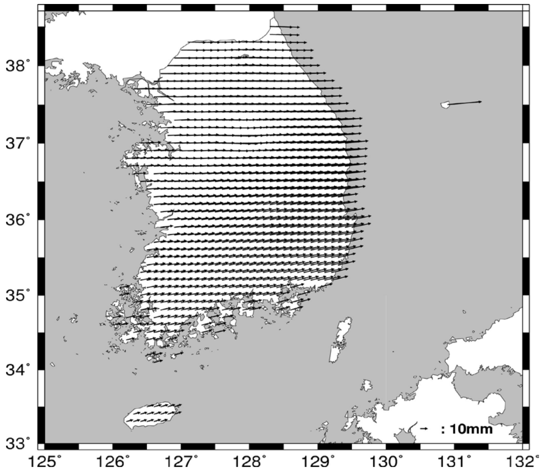

Fig. 9. Crustal deformation model in South Korea for the Tohoku Earthquake (longitude and latitude, with 2-minute intervals)

4. Accuracy of the Update Survey Results of the Unified Control Points Using the Crustal Deformation Model

In this study, the survey results of the 1,195 unified control points installed before the Tohoku Earthquake were recalculated using the developed crustal deformation model. The accuracy of the survey results recalculated using the model was evaluated using the GNSS data of the 119 common points resurveyed by NGII from 2012 (Fig. 10). The survey results of the 119 points were calculated based on the GNSS CORS survey results newly obtained after the quake as cited in section 2.2. In the graph in Fig. 11, the dotted line represents the difference in the survey results before the application of the crustal deformation model, and the full line represents the difference after the application of the model. As can be seen in Fig. 11, the difference from the actual survey results was reduced after the model was applied. Statistically, the

Table 7. Survey results at common points before and after application of the crustal deformation model

	Before (mm)	After (mm)
average	13.0	3.0
standard deviation	6.3	1.9
maximum	39.0	10.0
RMSE	14.1	3.4

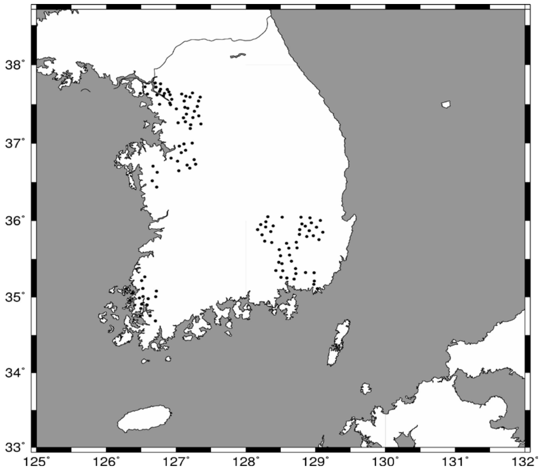

Fig. 10. Distribution of common points for evaluating the crustal deformation model

RMSE was reduced by approximately 10 mm, the maximum survey result difference dropped from 39 to 10 mm, and the number of excessive survey result differences of over 20 mm declined dramatically (Table 7).

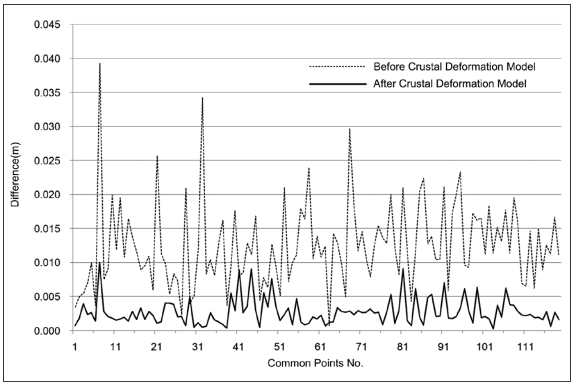

Fig. 11. Differences between survey and actual results before and after application of the crustal deformation model

5. Conclusion

This study estimated the crustal deformation in South Korea caused by the 2011 Tohoku Earthquake through a detailed analysis of GNSS CORS data. A crustal deformation model was developed in South Korea, and the survey results of unified control points changed by the quake were revised. Accuracy of the survey results of unified control points revised using the crustal deformation model was evaluated by comparing the revised results with the GNSS survey results after the quake. Below are the conclusions obtained through this study.

1) Analysis of data from the 72 stations among all the GNSS CORS installed in South Korea showed that the crustal deformation in South Korea caused by the Tohoku Earthquake had an average of 22.42 mm, a maximum of 55.7 mm, and a minimum of 9.2 mm. The direction of crustal deformation was towards the epicenter of the quake, and the magnitude of the crustal deformation tended to decrease linearly with the distance from the epicenter.
2) The Tohoku Earthquake was found to have caused changes in the survey results of the control points in South Korea. A crustal deformation model using the least square method was developed for the prompt revision of the modified survey results. The survey results of the 1,195 unified control points installed before the quake were revised using the crustal deformation model.
3) The accuracy evaluation of the crustal deformation model using the survey results of the 119 points obtained after the quake revealed that the RMSE declined from 14.1 to 3.4 mm, and that the maximum survey result difference dropped from 39 to 10 mm.
4) The accuracy of the crustal deformation model was found to be excellent as the crustal deformation caused by the Tohoku Earthquake showed an ideal linear distribution. However, this can also be considered a limitation of this study. The accuracy of the crustal deformation model needs to be evaluated further against various earthquakes.

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