Tsunami records due to the 2010 Chile Earthquake observed by GPS buoys established along the Pacific coast of Japan

Teruyuki Kato¹, Yukihiro Terada², Hitoyoshi Nishimura², Toshihiko Nagai³, and Shun'ichi Koshimura⁴

¹Earthquake Research Institute, The University of Tokyo

²Kochi National College of Technology

³Port and Airport Research Institute

⁴Graduate School of Engineering, Tohoku University

(Received February 8, 2011; Revised May 3, 2011; Accepted May 6, 2011; Online published August 15, 2011)

A GPS buoy operating about 10 km west of Cape Muroto, southwest Japan, recorded the tsunami due to the 2010 Central Chile Earthquake (M_w 8.8) that occurred on 27 February, 2010. The tsunami due to the Chile Earthquake arrived at the GPS buoy almost one day after the earthquake. The first peak of the tsunami was about 12 cm above the mean sea level. The second peak arrived about one hour and 46 minutes later and was about 20 cm higher than the mean sea level, which was the highest peak among the series of the tsunami waves. The later phases of recognizable tsunami waves continued for about one day after the first arrival of the tsunami. Comparison of these tsunami records with numerically-predicted tsunami suggests that the observed tsunami arrived about 30 minutes later than the arrival time predicted by the numerical simulation. If we manually shift the record on the time series, we find that a longer term of about 1 hour period components fit very well whereas a shorter term of 10–30 minutes of tsunami components shows significant phase shifts. This difference of phase shifts might be due to the effect of dispersion of the tsunami wave.

Key words: GPS, RTK, tsunami, GPS buoy, Chile tsunami, numerical simulation.

1. Introduction

A large interplate earthquake of M_w 8.8 occurred along the Chile trench at 06:34:14, 27 February, 2010 (UTC), according to USGS, which is at 15:34:14 on the same day by Japanese Standard Time (JST). A significant tsunami was generated by the earthquake and travelled across the Pacific Ocean arriving at the Pacific coast of the Japanese Islands almost one day after the earthquake. The tsunami was recorded by a number of sea-level measuring instruments that have been deployed in the whole area of the Pacific. Here, we show the record obtained at the GPS buoy sited near Cape Muroto, southwestern Japan, and we compare the observed record with the record estimated by a numerical simulation.

2. History of the Development of the GPS Buoy

For over 12 years we have developed the GPS buoy for detecting tsunami given that the early detection of tsunamis contributes to mitigating tsunami disasters (e.g., Kato *et al.*, 2000, 2008). The system employs a real-time kinematic (RTK) GPS in which a GPS antenna is situated at the top of a buoy floating on the offshore ocean surface, while another antenna is situated at a ground base station near the coast (Fig. 1). A sampling frequency of 1 Hz is used to monitor the sea surface changes. The data obtained at the buoy is transmitted to the ground base station using radio and a

baseline analysis is made in real-time by a PC using both the buoy data and the data taken at the base station. Assuming that the coordinate of the base station is known, the precise position of the buoy can be determined to better than a few centimeters of accuracy.

The determined positions of the buoy applies not only to the case of a tsunami but also for all kinds of sea surface changes including wind waves, tides, etc. In order to extract the relevant components of a tsunami, the record is applied with a low pass filter using a simple moving average of 120 seconds. Tides are also removed by subtracting a tidal component calculated using harmonic analysis of 90 days of data at the position of the buoy. Since the accuracy of such a harmonic analysis would be a few centimeters if no anomalous sea surface deviation occurs such as that due to the passage of low pressure or variations of current, tsunami data can be extracted with a certain accuracy if the tsunami perturbation exceeds a few centimeters (e.g., Shimizu *et al.*, 2006). Both long period and shorter period waves are communicated via the dedicated webpage (<http://www.tsunamigps.com/gpsreal.php>).

The operational system was first deployed off Ofunato, northeastern Japan, in 2001. This system successfully recorded two tsunamis due to the June 23 (UTC) 2001 Peru earthquake (M_w 8.4) and the September 25 (UTC) 2003 Tokachi-Oki earthquake (M_w 8.3). Both records showed clear tsunami wave traces with about 10 cm of maximum height. After three years of operation, the system was abolished and a new GPS buoy was established about 10 km south off Cape Muroto, southwestern Shikoku, Japan, on

Fig. 1. GPS buoy system for detecting tsunami. RTK-GPS is employed together with radio transmission and an internet dissemination system, so that anyone can observe tsunami in real time.

Fig. 2. Location of the GPS buoy established about 10 km west of the Cape Muroto (upper left inset). Stations colored in dark brown are used for Fig. 5.

April 11 2004. The buoy recorded the tsunami due to the September 5 (UTC) 2004 Off Kii Peninsula earthquake (M_w 7.4) (Kato *et al.*, 2005). This system sank as a result of an accident in March 2006 and a new GPS buoy was established in April 2008. The current GPS buoy is now operational at about 10 km west of Cape Muroto, southwestern Japan. The location of the buoy is shown in the inset of Fig. 2 and the design of the buoy is shown in Fig. 3. The distance between the buoy and the land base station is about 13 km.

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has established a GPS buoy system for monitoring sea waves, with eleven GPS buoys along the Pacific coast of Japan, since the year 2008 as a part of the Nationwide Ocean Wave information network for Ports and HarbourS (NOWPHAS) system (<http://www.mlit.go.jp/kowan/nowphas/>). All of these GPS buoys are located within 20 km from the coast. More than 14 GPS buoys have been established in this project, of which twelve buoys are in place and in operation along the

Fig. 3. GPS buoy established west of Cape Muroto, southwest Japan. The system has been operational since April 2008. (left) photo, (right) plan (unit: mm).

Fig. 4. Location of the 2010 Chile Earthquake shown by an asterisk and the estimated vertical displacements. See text for the source parameters.

pacific coast of the Japanese Islands as of February 2011 (Fig. 2).

3. Tsunami Record due to the 2010 Chile Earthquake

The 2010 Central Chile earthquake generated a significant tsunami. In order to make numerical simulations, we employed the USGS source model and assumed the following fault parameters: source dimension ($L \times W$) (450 km $\times$ 100 km), dislocation (15 m, uniform), mechanism (Strike, Dip, Rake) = (16, 14, 104) referenced to the USGS model. Figure 4 shows the source location and the vertical deformations due to the earthquake, which was used for the numerical simulation of the tsunami propagation.

Figure 5 shows the observed tsunami record of the low-pass filtered component of the vertical sea surface change at the Muroto GPS buoy. The effect of tide is also removed from the filtered record. It is readily visible that the tsunami

Fig. 5. Recorded vertical motion of the GPS buoy during the tsunami (black) and simulated record (red). The simulated record is offset forward by 26 minutes.

due to the Chile Earthquake arrived at the GPS buoy at around 15:22 on 28 February (JST), which is nearly one day after the earthquake occurred. The first peak of tsunami is about 12 centimeter above the mean sea surface height. The second peak arrived about one hour and 46 minutes later with about 20 cm height, which was the highest peak among the series of tsunami waves. The later phases of recognizable tsunami waves continued for about one day after the first arrival of the tsunami.

4. Comparison with Numerically Simulated Data

The tsunami record was compared with a numerically-simulated tsunami after removing shorter and longer periods of waves. The numerical modeling of mid-ocean tsunami propagation was carried out using the finite difference method of the linear shallow-water wave theory with a Coriolis force in a spherical co-ordinate system (Nagano *et al.*, 1991). For tsunami modeling, we used the digital bathymetry data (GEBCO; Monahan, 2008) to resample and created a 5 arc-min grid. The modeled tsunami waveform at the GPS buoy is shown in Fig. 5 with the plot of the observed record after tide and wind-wave components have been removed.

Note that the modeled tsunami waveform has been manually shifted by 26 minutes to fit to the observed one, because a direct comparison suggested that the observed tsunami arrived about 26 minutes later than the arrival time predicted by the numerical modeling. We find that the longer period components of the tsunami of about 1 hour fit very well whereas the components of a shorter period of 10–30 minutes show significant phase shifts. The difference in arrival times of about 30 minutes is under investigation by considering various factors such as the sea bottom topography features on the path of the tsunami propagation, the spatial resolution of gridding, modeling errors, etc. The reason that the longer wave fits well with 30 minutes of phase shift while a shorter wave does not may be due to the effect of dispersion of the tsunami wave resulting in the longer wave propagating more rapidly than a shorter wave. Slip heterogeneity of the source might also be responsible for such dispersion, though the examination of these effects are left for future studies.

Fig. 6. Comparison between observed (black) and simulated tsunami (red). About 30 minutes of offset may be seen for all of the stations. The reason for this offset is under investigation.

The GPS buoys of the NOWPHAS system at eleven sites also recorded tsunamis with 20 to 30 centimeters of maximum height (see also: <http://www.mlit.go.jp/kowan/nowphas/>). The tsunami record is processed similarly as the record taken at the Muroto GPS buoy (Kawai *et al.*, 2010). Comparisons of the NOWPHAS records with the numerical model are conducted at eight NOWPHAS buoy stations: East Off Aomori, Off Central Iwate, Off South Iwate, Off North Miyagi, Off Central Miyagi, Off Owase, SW Off Wakayama, and West Off Kochi. The results are shown in Fig. 6. These results indicate a similar tendency as the record at the Muroto GPS buoy shown in Fig. 5.

5. Discussion

The GPS buoy system introduced in this study successfully detected the tsunami due to the 2010 Chilean Earthquake. Its amplitude and phase are generally consistent with the predicted tsunami waveform. However, there are some inconsistencies with the simulated data. First of all, the arrival time of the tsunami was about 30 minutes later than the predicted arrival time. This difference was unanimously observed at all GPS buoys that are established along the Japanese coast. Comparisons by other studies (e.g., Satake *et al.*, 2010) show similar results.

The difference of arrival times of about 30 minutes may have to be investigated by considering various factors such as the water depth model, the spatial resolution of gridding, modeling errors, as well as the source location. The prediction of tsunami heights is fairly consistent with observed heights, suggesting that the prediction of inundation height at the coast may be made with considerable precision. Further improvements of the numerical simulation may be necessary for a better prediction of tsunami arrival time and

the differential effects of arrival times due to dispersion between long period and short period sea waves.

When a comparison between a numerical simulation and observation is being carried out, one significant advantage of a GPS buoy compared with a coastal monitoring system such as tide gauges is that the GPS buoy is less affected than tide gauges by local geomorphological effects or non-linear effects due to basal friction, etc. Moreover, a GPS buoy can record not only tsunami but also wind waves. Therefore, a GPS buoy can be utilized for daily sea surface monitoring, and not just for tsunami.

Currently, the GPS buoy system uses RTK-GPS which requires a land base for the precise positioning of the buoy. This limits the distance of the buoy from the coast to, at most, 20 km. Establishment of the buoy further from the coast is truly important to achieve a longer lead-time for evacuating nearby coasts. There are two problems to be solved in this regard; one concerns accuracy and the other data transmission. Since tsunami amplitudes decrease as water depths become larger, the detectability requirement of a GPS buoy is more demanding in deeper ocean. If the distance of a GPS buoy from the coast is larger, currently used RTK-GPS may not achieve centimeter accuracy. We are trying to introduce another algorithm for solving this problem. One possibility is the so-called precise point positioning algorithm in which a baseline is not used for estimating the position, but only a single station is used (Geng *et al.*, 2010a, b). We are now testing if such an algorithm can achieve centimeter accuracy in the current GPS buoy system.

Another problem of deployment further from the coast would be data transmission. Currently, we are using radio for data transmission. Since we use a dual radio band, data transmission is very reliable; data have been acquired without loss of lock in rough water, even close-by the passage of a typhoon. However, radio transmission would not be feasible, if the distance of the GPS buoy is far from the coast, say more than 50 km. Satellite data transmission would be more reliable in such a situation. However, such satellite data transmission is still not cost-effective. Future cost reduction of satellite data transmission is truly needed for earlier tsunami detection.

6. Conclusion and Remarks

The GPS buoy that has been operated nearby Cape Muroto, southwest Japan, successfully detected a tsunami due to the February 2010 Chile Earthquake. The maximum amplitude of the tsunami was about 20 cm from crest to zero in height. The tsunami had also been recorded at all the other GPS buoys established as part of the NOWPHAS system along the Japanese coast.

In order to use a GPS buoy for tsunami disaster mitigation, however, there are still some problems to be solved. One such problem is that the numerically simulated record predicted tsunami arrived about 30 minutes earlier than the observed tsunami. The causes of such a difference require clarifying and numerical simulation modeling should be improved. Also, the deployment of buoys further from the coast is indispensable for earlier detection and the evacuation of people. When such problems are solved, an array of

GPS buoys for monitoring tsunami will provide us a powerful tool for mitigating disasters due to tsunami.

Finally, a very large earthquake of M_w 9.0 occurred offshore of the northeastern part—known as Tohoku—of Japan and a huge tsunami of more than 30 meters of run-up heights devastated the whole area along the Pacific coast of Tohoku. The earthquake and tsunami caused more than 20,000 people to be accounted as dead or missing. The GPS buoys that were deployed a few years before the earthquake by the Ministry of Land, Infrastructure and Tourism (MLIT) recorded significant tsunami higher than 6 m at the offshore South Iwate (near Kamaishi City) before its arrival at the coast (Takahashi *et al.*, 2011). The records at the GPS buoys were monitored at the Japan Meteorological Agency and led to an updated tsunami early warning of more than 10 meters at the coast. Detailed investigations of the tsunami and the effectiveness of the GPS buoys are still underway and will be reported elsewhere.

Acknowledgments. The authors are indebted to Dr. Daisuke Tatsumi and Dr. Hiroyasu Kawai of the Port and Airport Research Institute for a discussion of the data of NOWPHAS GPS buoys. The observed data of Fig. 6 was provided by the Ministry of Land, Infrastructure and Tourism (MLIT). This work was supported by Grant-in-Aid for Scientific Research (S) 21221007.

References

- Geng, J., X. Meng, A. H. Dodson, M. Ge, and F. N. Teferle, Rapid re-convergences to ambiguity-fixed solutions in precise point positioning, *J. Geod.*, **84**(12), 705–714, 2010a.
- Geng, J., F. N. Teferle, X. Meng, and A. H. Dodson, Towards PPP-RTK: ambiguity resolution in real-time precise point positioning, *Adv. Space Res.*, doi:10.1016/j.asr.2010.03.030, 2010b.
- Kato, T., Y. Terada, M. Kinoshita, H. Kakimoto, H. Issiki, M. Matsuishi, A. Yokoyama, and T. Tanno, Real time observation of tsunami by RTK-GPS, *Earth Planets Space*, **52**(10), 841–845, 2000.
- Kato, T., Y. Terada, K. Ito, R. Hattori, T. Abe, T. Miyake, S. Koshimura, and T. Nagai, Tsunami due to the 2004 September 5th off the Kii peninsula earthquake, Japan, recorded by a new GPS buoy, *Earth Planets Space*, **57**, 297–301, 2005.
- Kato, T., Y. Terada, T. Nagai, K. Shimizu, T. Tomida, and S. Koshimura, Development of a new tsunami monitoring system using a GPS buoy, *Proc. Int. Symp. on GPS/GNSS 2008*, 846–851, 2008.
- Kawai, H., M. Satoh, T. Nagai, and K. Kawaguchi, Analysis on shallow-water transformation of the 2010 Chilean tsunami on the Japanese coast by GPS buoy network, *Rep. Port Airport Res. Inst.*, **49**(4), 2010 (in Japanese with English abstract).
- Monahan, D., Mapping the floor of the entire world ocean: the General Bathymetric Chart of the Oceans, *J. Ocean Tech.*, **3**, 108, 2008.
- Nagano, O., F. Imamura, and N. Shuto, A numerical model for far-field tsunamis and its application to predict damages done to aquaculture, *Nat. Hazards*, **4**, 235–255, 1991.
- Satake, K., S. Sakai, T. Kanazawa, Y. Fujii, T. Saito, and T. Ozaki, The February 2010 Chilean tsunami recorded on bottom pressure gauges, presented at the JpGU 2010 meeting (May 23–28 2010 at Makuhari, Chiba, Japan), MIS050-P05, 2010.
- Shimizu, K., T. Nagai, J. H. Lee, H. Izumi, M. Iwasaki, and T. Fujita, Research on realtime tsunami detection system using offshore water surface elevation data, *Ann. J. Civil Eng. Ocean*, **22**, 523–528, 2006 (in Japanese with English abstract).
- Takahashi, S. and other 33 co-authors, Urgent survey for 2011 Great East Japan earthquake and tsunami disaster in ports and coasts, *Technical Note of the Port and Airport Research Institute*, No. 1231, 200 pp., 2011 (in Japanese with English abstract).