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Offshore Wave, Tsunami and Tide Observation Using GPS Buoy

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1. INTRODUCTION

Offshore observation of tsunami and storm surge before arriving to the coast is very important for coastal disaster prevention. But up to ten years ago, coastal tide stations had been supposed to be the only means to observe tsunami and storm surge profile, for difficulty of offshore observation (Goda.et.al., 2002). Recently seabed installed coastal wave gauges have been repeatedly reported to successfully observe various tsunami profiles by conducting continuous data acquisition (Goda.et.al., 2001; Nagai, 2002a; Nagai.et.al, 1996, 2000, 2002b).

Nevertheless seabed installed types of wave gauges are installed in the limited area with water depth less than 50m for their maintenance necessity. On the other hand, buoy type wave gauges with acceleration sensors are not able to detect long period tsunami and storm surge, for acceleration is very small in such long period fluctuations. Therefore, a new offshore observation system has been desired.

Authors recently developed new offshore observation system using GPS buoy, which does not need seabed maintenance human works and which can be installed in any sea area without water depth limitation. Long term field test of the GPS buoy started in the year of 2001 at the off-Ofunato-Port area (Kato.et.al., 2001). This paper explains results of the field test and discusses the obtained data reliability from a point of wide frequency range from short period wind waves to long period astronomical and meteorological tides.

Observed GPS buoy data were compared with Ofunato port tide station data obtained by Japan Meteorological Agency, and Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) coastal wave stations' data. NOWPHAS is Japanese wave information network established and operated by the Ports and Harbors Bureau of the Ministry of Land, Infrastructure and Transport, and its associated agencies including the Ports and Airports Research Institute (PARI) (Nagai.et.al.,1994; Nagai, 2002b).

2. FIELD TEST OFF THE OFUNATO PORT

Fig. 1 shows location of Ofunato port and NOWPHAS wave stations used for the data comparison, and Fig. 2 shows the map of the Ofunato port area. Coastal wave observation data at three NOWPHAS stations, Kuji station of 50m depth, Kamaishi station of 49m depth and Sendai station of 20m depth, were used for the comparison. The GPS buoy was set 3km off the on land station at 53m depth. To secure good accuracy of the buoy motion measurement with cm order, Real Time Kinematic (RTK) system was used with on land station. Vertical and two components of horizontal GPS buoy displacement were recorded with 1 second time interval

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continuously. Tide station of the Ofunato port is located on the coast near the on-land GPS station.

Fig. 3 shows the GPS buoy dimension. The buoy is moored with 4 sets of steel chains. The height of the GPS antenna was 6.4m above the sea surface. Therefore, the measured antenna displacement does not exactly coincide to the displacement of the central gravity point of the buoy. Effect of the rolling motion of the buoy should be included in the data.

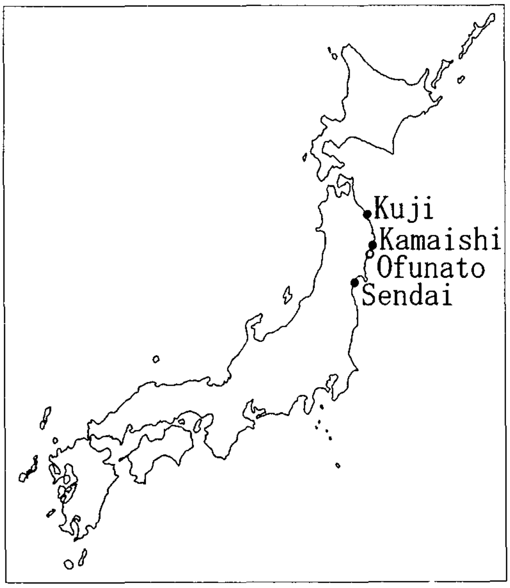

Fig. 1. Location of Ofunato Port and NOWPHAS Wave Stations.

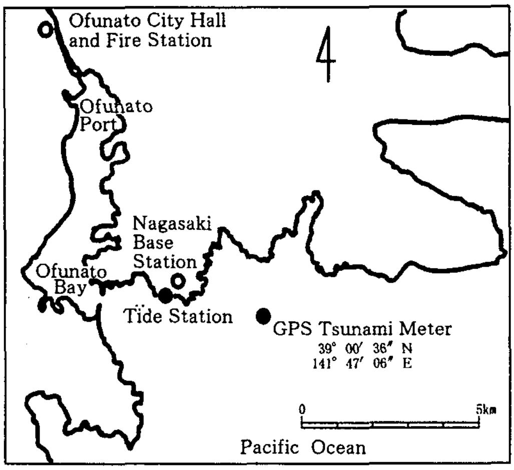

Fig. 2. Map of Ofunato Port Area.

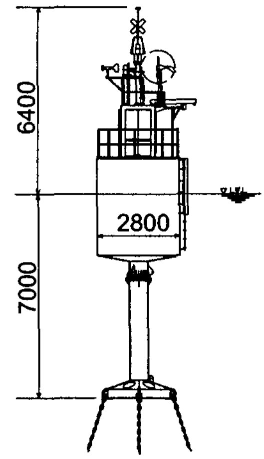

Fig. 3. GPS Buoy Dimension.

3. WAVE OBSERVATION RESULTS

Abnormal records were included in some part of the data transmitted every 1 second from the GPS buoy due to wireless data transmission errors from the buoy to the on land station. Nevertheless with application of data processing method used in NOWPHAS (Goda. et.al.2001), significant wave heights and periods are to be obtained, by omitting abnormal parts of the data. Therefore authors tried to obtain significant waves every 2 hours during 20 minutes' data, 10 minutes before and after even number hours.

Fig. 4 shows significant wave record during the year of 2001. Horizontal axis means the 365 days from January 1 to December 31, and vertical axis means 12 times observations every day. The blank mark means that significant waves were successfully obtained and the x mark with failure due to some abnormal data transmission. Below the figure, the normal data ratio is shown. Fairly high ratio of annual 82% is seen by excluding three long-term troubles during January, April to May and the end of December, which is supposed to be successful data acquisition ratio for the first stage of field experiment.

Table 1 shows comparison of observed annual three highest wave conditions of the GPS buoy and the simultaneous NOWPHAS wave records (Nagai.et.al, 2003), with meteorological causes. When high wave conditions were observed at the GPS buoy, NOWPHAS coastal stations also recorded high waves, which proved reliability of GPS buoy wave observation.

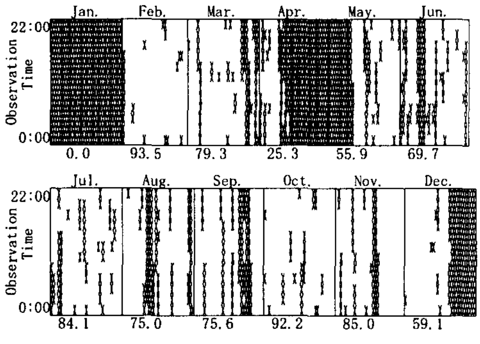

Fig. 4. Significant Wave Record Ratio.

Table 1. Observed High Wave Conditions

Date and Time		2001. 3.4.22:	2001. 10.11.18:	2001. 8.23.6:
Cause		Dowble Low Pressures	Dowble Low Pressures	Typhoon0111
Ofunato Buoy	H1/3(m)	4.06	3.66	3.30
	T1/3(s)	12.0	11.0	10.4
KujiSt.	H1/3(m)	3.95	3.42	2.98
	T1/3(s)	11.5	10.5	9.8
Kamaishi St.	H1/3(m)	2.26	3.45	1.71
	T1/3(s)	9.3	10.1	8.6
Sendai St.	H1/3(m)	3.59	3.95	3.18
	T1/3(s)	10.2	10.4	9.9

Fig. 5 compares monthly and annual averaged significant wave at each wave station. Fairy good agreement can be seen among the stations, which also indicated reliability of the wave observation of the GPS buoy.

Fig. 6 compares time history of significant waves during the highest wave term in the year. Time history of wave growth and subsidence also well agreed among the stations.

Fig. 7 is an example of directional spectrum comparison of the GPS buoy at Ofunato and Doppler-type Wave Directional Meter (DWDM) (Goda.et.al.2001; Nagai,2002b) at Kuji at 22:00 observation on March 4th, the highest wave record during the year at Ofunato buoy. Although the peak frequency coincides between the two stations, directional distribution of wave energy was completely different. Double spectrum peaks from south and north direction were seen at Ofunato, which seems extraordinary, for wave energy attack from the land direction north is incredible. Supposedly the reason is due to the difference of GPS antenna location and central gravity point of the buoy. New analysis method may be necessary to obtain correct directional waves from the GPS buoy with consideration of rolling motion of the buoy to compensate the different displacement of the buoy center and the antenna.

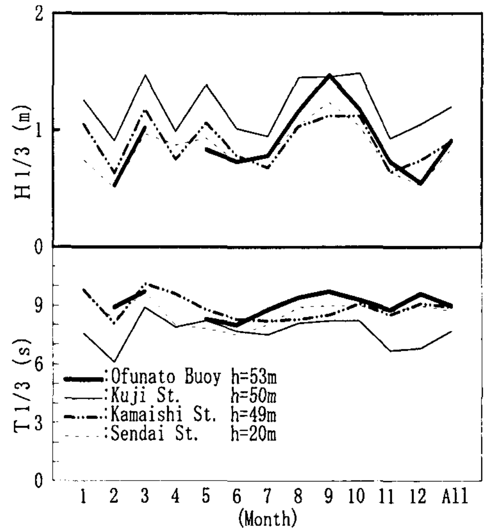

Fig. 5. Monthly and Annual Averaged Significant Wave.

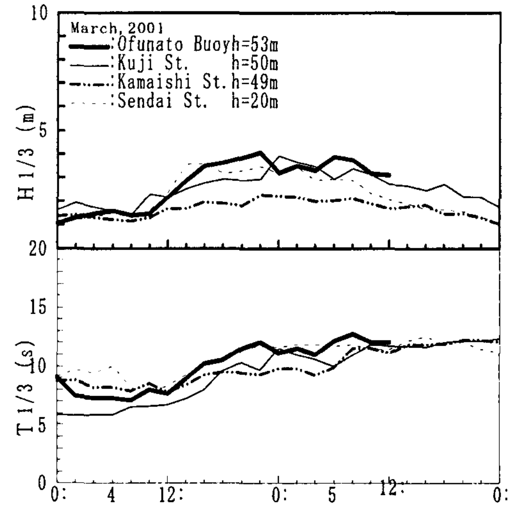

Fig. 6. Time History of Significant Waves during High Wave Term.

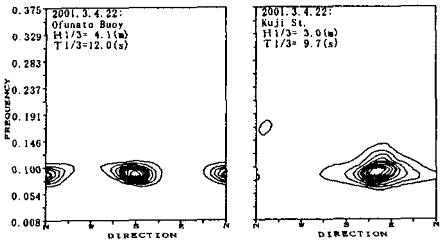

Fig. 7. Directional Spectrum Comparison.

4. TSUNAMI OBSERVATION RESULTS

Tsunami is very rare event. Therefore it was supposed to be difficult to obtain offshore tsunami data during the limited field experimental term. But actually one long distance tsunami caused by the 2001 Peru earthquake of the magnitude 7.9 was observed on June 25, 2001.

Fig. 8 shows the observed tsunami records during three days from June 24 to 26. Frequency banded wave height expression for infra-gravity wave observation based on 2 hours' data spectrum analysis applied in the NOWPHAS system is used in the Fig. 8 (Nagai, 2002b; Nagai.et.al.2002). Only the lowest frequency banded wave heights with corresponding period longer than 600s (10min.) shows abnormal increase around 6:00 on June 25, when the tsunami was numerically estimated to arrive at Japanese Pacific coasts, not only at the Ofunato GPS buoy but also at NOWPHAS Kuji station. This means that the tsunami period was longer than 10 minutes. The relatively high low frequency tsunami waves with corresponding wave height around 10cm continued half days and gradually decreased after that at both stations. This proves that GPS buoy successfully observes offshore tsunami profiles as the seabed installed coastal wave gauges do.

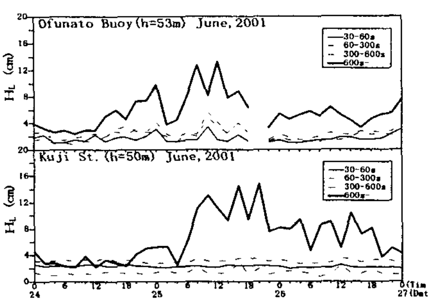

Fig. 8. Long Period Frequency Banded Wave Heights.

5. TIDE AND STORM SURGE OBSERVATION RESULTS

Harmonic tidal analysis was also tried to the annual GPS buoy data, and the results were compared with the coastal tide station data. Table 2 and Table 3 show the amplitude and phase of the harmonic analysis respectively, where offshore means results obtained from the GPS buoy data and Coastal means ones obtained from the coastal tide station of Japan Meteorological Agency. Coastal harmonic constants are to be obtained from published books based on data several years ago (Hydrographic Department of Japan Maritime Safety Agency, 1992; Japan Meteorological Agency, 2000). Nevertheless authors estimated them directly from the observed data in 2001 by conducting harmonic analysis calculation, for harmonic constants slightly differ year by year (Nagai.et.al, 1998).

Table 2 shows that amplitudes of the principal four components of astronomical tides at offshore are about 80% values of that at on-coast. This means that low frequency sea level fluctuation such as tide increases its amplitude from offshore to on-shore, which is very important fact for coastal disaster prevention points of view.

Table 3 shows that tide phase offshore is about 10 minutes advanced than that of on-coast in every principal components. This means that GPS buoy is able to detect low frequency water level change such as storm surges 10 minutes before arriving to the coast, which indicates that offshore GPS buoy will give us very important coastal disaster information before suffering damages in coastal area.

Fig. 9 shows water surface level time history at offshore and at on-coast before and during the typhoon No.0115 passed near from September 10 to 11, 2001. Upper two figures show comparison of observed and estimated water level offshore and on-coast respectively, where estimated water level is calculated from the annual harmonic constants. Estimated level is to be considered as astronomical tide. Difference between observed and estimated means tide deviation shown in the lowest figure due to meteorological effects such as air-pressure decrease and water mass transport due to winds.

During the day of September 10, when the typhoon located far from the Ofunato port and the typhoon effects were relatively small, observed and estimated water levels almost agreed both offshore and on-coast without detecting deviation. Nevertheless during the day of September 11, when the typhoon passed near the Ofunato port, obvious increase of deviation was seen at both offshore and on-coast observation. The maximum deviation was about 30cm at both stations around midnight of September 11 to 12. This indicates that GPS buoy detected the storm surge correctly due to typhoon passing.

Table 2. Harmonic Components' Amplitude

Constant	Amplitude (cm)		
	Offshore	Coastal	Ratio
M_2	24.4	30.5	0.80
S_2	11.9	14.0	0.85
K_1	19.7	23.5	0.84
O_1	15.7	18.5	0.85
Z_0	71.7	86.5	0.83

Table 3. Harmonic Components' Phase

Constant	Phase (°)			
	Offshore	Coastal	Angle Difference	Time Difference
M_2	104.7	97.8	6.9	14.3min.
S_2	138.3	133.7	4.6	9.2min.
K_1	164.5	160.2	4.3	17.2min.
O_1	147.4	143.7	3.7	15.9min.

6. CONCLUDING REMARKS

GPS Buoy successfully observed sea surface fluctuation of wide frequency range, including wave, swell, tsunami, storm surge and astronomical tide, with good precision in the long-term Off-Ofunato-Port field test. Installation of the GPS buoy to the deeper offshore area is desirable in order to observe tsunamis and storm surges more promptly than ever for the safe management of coastal zone.

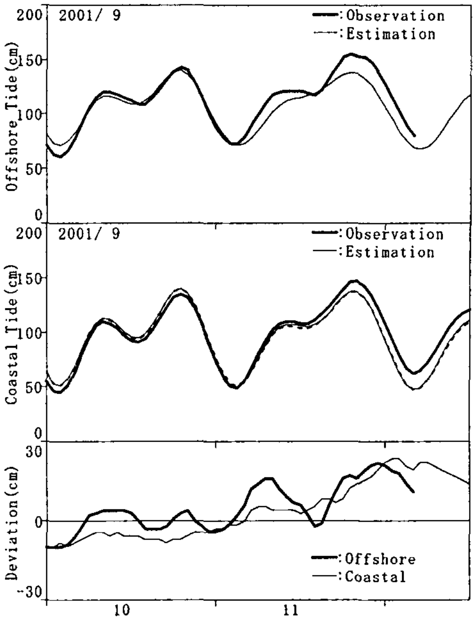

Fig. 9. Observed and Estimated Tide Level and Deviation.

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