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Power spectral density analysis of ocean wave by using GPS buoy

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Abstract: Wave buoy equipped with a mechanical or electrical sensor have been used extensively to observe waves around the world but the integration of GPS technology with wave buoy (GPS buoy) only has been explore usefulness in this field in the early 90's. This study presents the capabilities of GPS buoy to observe wave data at Strait of Malacca by using high precision kinematic positioning approach. The GPS buoy data obtained from this observation were processed through a precise, medium-range differential kinematic technique. These data were observed at a high rate (1 Hz) interval over a period of more than 24 hours from a nearby coastal site. The kinematic coordinates of the GPS buoy were estimated via epoch-wise pre-elimination and the backward substitution algorithm. These kinematic coordinates are used to calculate the magnitude of the Power Spectral Density (PSD). PSD analysis function able to shows the strength of the variations (energy) as a function of frequency. The tidal changes and monsoon wind has been found to greatly influence the wave energy as shown in the PSD analysis. From the test result, GPS buoy and data processing technique promises a total solution as a complete ocean wave monitoring solution for Strait of Malacca.

Keywords: GPS buoy, kinematic positioning, power spectral density, ocean tidal, monsoon wind

1. Introduction

Malaysia is surrounding by ocean with total of coastline of 4,675 kilometres, whereby divided by two distinct parts which is Peninsular Malaysia and East Malaysia, separated from each other by the South China Sea. The west part of Peninsula Malaysia is also facing the Strait of Malacca [1]. The coastal zone of Malaysia has a special socio-economic and environmental significance. More than 70% of the population lives within the coastal area and a lot of economic activities such as urbanization, agriculture, recreation and eco-tourism, fisheries, aquaculture and oil and gas exploration are situated in the area. With a large percentage of population living within 5 km from it, demands of developments and industrialization in these areas had made a very big impact on the resources and the coastline itself [2]. Generally, the coast zone plays a huge factor in development of the country, but it facing a constant threat from erosion.

The National Coast Erosion Study, which began in 1984 and completed by 1986 was the first comprehensive study carried out to assess Malaysia shoreline. The study reported that, 52% of the coastline in the east coast of Peninsular Malaysia is being eroded and in the west coast, 50% of the coastline is being eroded [3]. The recent study has revealed that about 29% of the total of 4800km of Malaysia shoreline was subjected to varying degree of erosion [4].

Coastal erosion is a natural phenomenon resulting from the interactions between natural process and the system. The natural process primarily responsible for coastal erosion is driven by waves. Ocean waves are capable of massive destruction and endless beauty. Unraveling the mysteries of their generation and predicting their height has been a pursuit of sea fairing people and coastal dwellers throughout history. There are many different kinds of open water waves; among them are wind waves, tides and tsunamis. Focus of this study is on wind waves and tidal waves.

It is really important to observe ocean wave to understand the factor influence the wave energy. By understanding these factors, early prevention can be taken to reduce coastal erosion. Therefore, various techniques have been employed for ocean wave observation such as the coastal water level gauges, bottom pressure gauge, satellite altimetry and wave buoy. This study will demonstrate the potential of Global Positioning System (GPS) buoy for ocean wave observation and PSD for ocean wave energy analysis.

2. Ocean Monitoring System

GPS buoy was designed by review some of the existing design and which are still actively used such as Datawell directional wave rider [5], Fugro Tsunami buoy series SEAWATCH Deep Sea Module [6] and Deep Sea MKI-3 buoy [7].

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2.1 GPS buoy and control station

The fabrication process was divided into several stages, which is material selection, fabrication of buoy, water proofing and anti-rust. The GPS buoy was constructed from a rubber-maid float to determine buoyant volume. A GPS antenna and a solar charger controller were installed in the GPS buoy; moreover, a steel pipe measuring 0.9 m with approximately 7.5 kg of ballast was fixed to the bottom of this buoy for stability and for minimizing its motion due to ocean waves. Prior to this fieldwork, the fully assembled GPS buoy was tested in the calm waters of the UTHM lake and a calibration measurement was taken to determine the height of the GPS antenna above the water line. Two Leica GPS receivers were used in the experiment. The buoy excels in all tests that have been done. Figure 1 shows two most important equipment in this study consist of GPS buoy and GPS control station.

Fig. 1 GPS buoy and FKAAS control station

2.2 Observation technique and data processing algorithm

The equipment used for field observation is Leica GS15 and software for data analysis is Bernese 5.0. The equipment and software been widely used in the field of geomatics for quite some time. In this study, the approach used in the measurement data is quite different where GPS antenna mounted on buoys to measure changes in sea surface level. This antenna record the signals from GPS satellite while buoy on the move with unpredicted movement patterns due to hit by sea waves. The antenna's ability to gather data in these situations is unknown. It can only be decided after the data observation in the same situation carried out. Therefore, a simulated wave observed in controlled conditions was conducted to get an overview of the capabilities of this equipment when observing data in real situations at sea.

As mentioned previously observed data were analyzed using the software Bernese 5.0. The software's ability to eliminate error and produce high precision results is not in doubt, but in this study the field observation situation is different where the data observed by moving gps antenna in unpredictable patterns require different data analysis techniques. Thus, the observed wave simulation data that has been made in a controlled condition has been processed by this software is to get the parameters that are appropriate to remove the errors to get the high precision results. Observation waves in a controlled condition intended to verify the equipment and data analysis technique was carried out using a slider machine.

A field test was conducted at three sites situated at different distances from the UTHM control station. Figure 2 shows the change in the position (z axis) of the antenna at these stations. The "wave" heights at all stations ranged from 0.31 m to 0.35 m while the control value observed by slider machine is 0.32 m. The wave patterns were uniform in all locations and only the data from the third station were a bit unstable in comparison with the first observation station. These differences may be contributed by the atmospheric and tropospheric variations during observation. The effect from these variations clearly shown by obvious different of root mean square (r.m.s.) values of each stations where rms for station 1 is 2.2 cm, station 2 is 2.9 cm and station 3 is 4.5 cm.

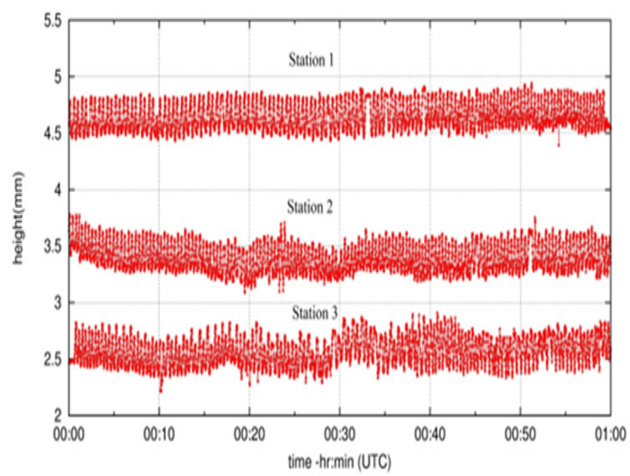

Fig. 2 Wave heights at the three stations as observed with the slider machine

This test has proven GPS receiver that was used to gather data able to measured high precision data even if the observations made in conditions that the GPS receiver is constantly moving. The accuracy obtained after comparisons were made with the actual value is very impressive showing this equipment suitable for use in actual observations at sea. The accuracy of the GPS receiver are also not affected by a significant difference between the location of the observations to a control station hence all wave height measured are almost the same as the control value of slider machine wave height. Based on the results and analysis carried out, the equipment and the algorithm that have been developed for the ocean wave monitoring system are ready for sea observation [8].

The first sea observation was done for "truth" comparison of sea level as measured by a digital tide gauge at a nearby buoy location. The digital tide was overseen by Geodesy Section Department of Survey and Mapping Malaysia (JUPEM). JUPEM is the government agency responsible for all survey works in Malaysia. The observation was conducted on March 13, 2014 at Kukup Port, Pontian, Johore. The GPS buoy was deployed about 500 m off the pier. The position of the GPS buoy was estimated relative to a fixed reference GPS receiver on the FKAAS control station, which was about 70 km away (figure 3). The GPS provided real-time 3D position relative to the reference station.

Fig. 3 Location map of the buoy, JUPEM tide gauge and FKAAS reference station

The local vertical component of the GPS solution was one of the sea level measures compared with the "truth" obtained through the tide gauge measurement. No comparable "truth" was available for the horizontal components of the GPS buoy. Based on the analysis, both methods were able to produce quite similar result. In sum, the ocean wave monitoring system demonstrates that the precise determination of sea surface height can be successfully achieved using the post-processing kinematic GPS technique. The centimeter-level agreement between the results of the two methods in ocean surface monitoring also suggests the future possibility of using this inexpensive and more flexible GPS buoy to improve (or even replace) tide gauge stations [9].

2.3 Field campaign

The field observation was conducted off the shore of Senggarang, Batu Pahat, Johor on October 14, 2014. A GPS buoy equipped was deployed approximately 3 km off the Senggarang Coast. The position of the GPS buoy was estimated relative to a fixed reference GPS receiver on the FKAAS control station, which was about 20 km away (figure 4). The observation has been done for 24 hours at high rate data logging (1Hz). During the observation the wind speed is moderate between 10 km/h to 20 km/h and the direction is keep changing. This is because of influence from inter monsoon season in month of March and October every year.

The data obtained from the fieldwork were processed by post-processing kinematic GPS positioning software based on the proposed methodology developed at the Astronomical Institute, University of Bern, Switzerland. Dual-frequency data must be obtained for linear ionosphere-free (Lc) resolution. Given that the program was designed for both post and real time data reduction, the GPS precise ephemeris technique was utilized by default to process data. The satellite elevation cutoff angle was set to 5°. Once phase ambiguities were successfully re-solved in the initialization procedure, L1 and L2 phase measurements were used to conduct continuous epoch by epoch kinematic positioning. When the number of continuously tracked satellites dropped below four, the program automatically reverts to the stage of ambiguity integer identification to determine the correct phase ambiguities [10 & 11].

Fig. 4 Field campaign location

Throughout the entire field campaign, the buoy constantly measured its location. The Cartesian co-ordinates (x, y, z) of the antenna reference point of the GPS buoy were readily converted into their corresponding geodetic quantities (□, □, h). The instantaneous water level was obtained after reducing the height component h from the antenna reference point to water level according to known antenna height information.

Then the GPS buoy position (x, y) is used to calculate the strength of the waves using PSD analysis. Input needed for PSD analysis is the magnitude of buoy. The magnitude values were calculated from the absolute difference of the buoy position (x, y) for every second. This is the value of buoy movement within one second period specified in unit of meters. PSD analysis was performed by using MATLAB software with special design toolbox for analyzing measured waves data. The results obtained from this analysis were shown in plotted graph of wave power and frequency of wave occurrence.

3. Results and Discussion

The value obtained from the PSD analysis plotted on a graph PSD value against frequency with the value provided in the Log form. Unit for the PSD is expressed in the form of m2s [12 & 13]. The analysis of PSD values was related to the wind and monsoon season. Figure 5 shows a graph of the PSD against frequency observed during the field observation.

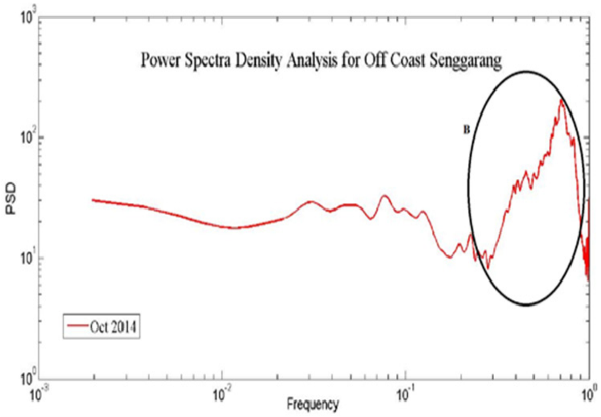

Fig. 5 PSD show sharp increase (marked by B) caused by tidal influence

The observations was made during the inter monsoon season. Based on these figures the PSD value during observations made increased uniformly throughout almost 80% of the observed frequency. At the rest of observed frequency, the changes of PSD value quite significant whereas the maximum and minimum value difference is 195 m2s. The obvious difference of PSD values as shown in the figure marked by (B) caused by tidal influence. As on the date of the observations the difference between low tides and high tides is 2.3 m are still large for offshore of Senggarang. The difference is causing the fast current movements during tidal changes that trigger a sharp increase in the PSD value.

Other than that, winds have also contributed to the increase of wave height during observations made. PSD highest value recorded during the observation made is 210 m2s occurring at a frequency of 10-0.2. PSD minimum value is 15 m2s was recorded at a frequency of 10-0.55. Whereas during the inter monsoon winds did not have a fixed direction and the speed keep changing. The effect of this wind can be seen on the inconsistent of PSD during the observations were made. Therefore, PSD value recorded during these two observations made are influenced by a large tidal differences and the weak monsoon wind at the observation site.

4. Summary

This study has successfully developed an ocean wave monitoring system that has high accuracy and suitable for use in Strait of Malacca. This has been proven by excellence result from the verification of equipment and data analysis techniques that have been carried out. The results has showed the combination of GPS receiver and data processing algorithms able to provide high accuracy result when compared with standard value.

The "truth" comparison results of observations using the GPS buoy with the existing methods, in this case is automatic tide gauges also successfully done. The results of this comparison showed that the observed data using the GPS buoy has been able to provide almost the same results in terms of the tidal pattern observed. From the accuracy comparison, the GPS buoy observation was able to provide sufficient result compare with automatic tide gauge observation. While in terms of data observation frequency, the capabilities GPS buoy to is far superior to this observation method.

Apart from testing the accuracy and precision, GPS buoy observations results were analyzed using PSD to demonstrate the usefulness of this data. Based on this analysis, found out that the wave power off the coast of Senggarang is influenced by monsoon winds and tide difference. Although lack of field data, the system has shown great potential in the oceanography study in Malaysia especially in providing an alternative method for wave observation. For future studies, more field observations need to be conducted before firm conclusion can be made by considering the factor of difference monsoon and tidal changes.

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