Comparison of Two Severe Storms in Terms of Wave Characteristics Based On Recorded Field Data

Alireza Jafari¹ , Nick Cartwright² , Peter Nielsen³

¹Griffith School of Engineering, Gold Coast Campus, Griffith University, Southport QLD 4215, Australia, a.jafari@griffith.edu.au

²Griffith School of Engineering, Gold Coast Campus, Griffith University, Southport QLD 4215, Australia, n.cartwright@griffith.edu.au

³ School of Civil Engineering, The University of Queensland, Brisbane St Lucia, QLD 4072, Australia, p.nielsen@uq.edu.au

Abstract

Understanding of storm wave behaviour is critical to the development of appropriate coastal hydrodynamic models to assess risk management and mitigation strategies in response to problems such as coastal inundation and erosion. This is becoming increasingly important in the present age of accelerated global warming where it is expected that there will be an increase in the intensity of severe weather events such as tropical cyclones. One of the main problems in storm wave predictions is the lack of availability of sufficient field data for used in calibrating and verifying models. Most of the existing models have been validated based on laboratory works and as such are not entirely representative of storm wave conditions experienced in the field. This paper, presents a novel approach to the collection and analysis of field data under two different storm events which hits south-east Queensland in 2009, namely Tropical Cyclone Hamish and an East Coast Low. Results of these two severe storms are added to a data set collected in calm condition and in order to extracting new formulation of γ_s .

Key Words: Storm Surge, Tropical cyclones, Monometer Tubes, Wave Setup

INTRODUCTION

This paper presents field data collected under storm conditions. All of the field work was done at 'The Spit on the Gold Coast, Australia. The Gold Coast has a sub-tropical climate located in south east Queensland and experiences tropical cyclones and East Coast Lows during the summer months. The research facility at The Spit (see Figure 1) provides the opportunity of collecting surfzone water level and wave data even under harsh storm conditions. "The Bunker" utilises an array of permanently deployed manometer tubes to observe both time-averaged (mean) water levels (MWL) and high-frequency pressure fluctuations due to wave action at

12 locations extending from 500m offshore in to 60m through the surfzone (Figure 2). Theoretical details of the system can be found in Nielsen and Dunn (1998) and a description of Research Bunker can be found in Cartwright et al. (2009) .

Figure 1. Research Bunker in The Spit, Gold Coast

METHODOLOGY

The manometer tube system is a simple but very robust means of measuring and monitoring wave trains while they travel from 500m offshore through the inner surfzone.

Figure 2. Sketch of manometer tube array, exerting suction make it possible for reading

Generally, the mean water surface level in the ocean is below the ground level at the land based monitoring station and so suction is applied in order to draw the water levels above ground. This is done in an enclosed system with each tube being subjected to the same degree of suction thus preserving the relative water level differences between each tube. The absolute level of all tubes is then converted to

the Australian Height Datum (AHD) by including a surveyed static water level into the manometer board system so that it also experiences the applied suction. The water level in water reservoir is exposed to atmospheric pressure, thus the column of water which climbed inside the reference board shows the amount of suction inside manometer system (see Figure 2).

High frequency water level fluctuations due to wind waves are recorded by connecting pressure transducers directly to the landward end of the tube system (Figure 2). The raw voltage output from each of the sensors is logged at 10 Hz using a data acquisition card connected to a laptop computer. The raw voltage data is then converted to a pressure head by means of a calibration equation derived from laboratory tests. However, the manometer tube systems behaves as a resonating system with one end of the tube open to the wave fluctuations and the other blocked by a pressure transducer (cf. Nielsen et al. (1993)). In order to correct for resonance effects, a gain function introduced is applied to convert the pressure observed at the landward end of the tube to a pressure at the seaward end of the tube. Nielsen et al. (1993) performed laboratory tests to establish the following empirical gain function for a similar tube system,

$$G = \frac{1}{\sqrt{\left[\cos^2\left(\frac{\pi \times f}{2f_0}\right) + \left[B_1 \frac{L \times f}{c} \left(1 + B_2 \sqrt{\frac{\nu}{f \times d^2}} \right) \right]^2 \right]}} \quad (1)$$

where, ν is fluid viscosity (for water $\nu = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$), f_0 is the lowest resonance frequency, i.e., $f_0 = 0.25 \times c/L$, c is speed of waves sound in flexible tubes which can define as

$$c = \frac{1}{\sqrt{\rho(K + D)}} \quad (2)$$

where, K is the compressibility of the fluid and D is the distensibility of the tube. B_1 and B_2 , are two dimensionless factors which initially introduced to be $B_1=0.58$ and $B_2=5.0$ by curve fitting over data obtained from 120m and 50m tubes. However, these two empirical factors, improved by performing extensive sets of laboratory test over 9 different tubes varying in length from 10m to 900m. Applying new dimensionless factor, B_1 and B_2 , and replot the GF, result shows very good agreement with Laboratory data. By curve fitting (see Figure 3) following relations can be extract from B_1 and B_2 in term of length over outer diameter ratio of tubes:

$$B_1 = \pi \times \left(\frac{L}{OD} \right)^{-\frac{1}{10}} \quad (3)$$

$$B_2 = \left(2 \times OD / t\right) \times e^{-6 \times 10^{-6} \times (L / OD)} \quad (4)$$

where, L is tube length, OD is tube outer diameter, ID is tube inner diameter, t is tube thickness.

Figure 3. B_1 and B_2 Values against Equations (3) and (4) respectively

After applying the Gain Function to the recorded data, seabed pressure obtained. The seabed pressure is then converted to a free surface fluctuation using the local approximation approach of Nielsen (1989) .

Nielsen (1989) used the concept of most existing wave theories that all surface waves are harmonic and can be define by a combination of suitable harmonic functions. Then for an irregular wave in the ocean, a local frequency for each individual point in time series of water elevation can be defined. For example, for linear wave theory which assumes waves to have sinusoidal shape like $y(t) = A_n \sin(\omega_n t - \phi_n)$, by considering three points y_{n-1} , y_n , and y_{n+1} the angular frequency for n^{th} point can be approximated by,

$$\omega_n^2 = \frac{-y_{n-1} + 2y_n - y_{n+1}}{\delta^2 y_n} \quad (5)$$

where δ is sampling time interval. Considering p as recorded dynamic pressure below water surface, the semi-empirical function for transferring dynamic pressure to water surface elevation defined as:

$$\hat{\eta}_n = \frac{p_n}{\rho g} \exp \left[A \left(\frac{z}{h} \right) - \frac{p_{n-M} + 2p_n - p_{n+M}}{g(M\delta)^2 p_n} \left(h + \frac{p_n}{\rho g} - z \right) \right] \quad (6)$$

with experimental factor related on depth of recording dynamic pressure

$$A\left(\frac{z}{h}\right) = 0.67 + \frac{0.34z}{h} \quad (7)$$

where, h is water depth, z is the elevation of the sensor used to measure the dynamic pressure and M is a smoothing factor whereby instead of using the first neighbours of n^{th} point to estimate the free surface elevation, the M^{th} neighbours are used to smooth out numerical noise introduced by the finites difference expression in equation (6).

DATA VERIFICATION

The recorded data is verified against data from a nearby wave rider buoy and tide gauge. For example, Figure 4 shows the comparison between the mean water level recorded by the monometer tubes and the nearby Maritime Safety tide gauge data. It is seen that the deeper water tubes closely match the observed tide levels and then the tubes in shallow water sit above the tide as expected due to the upward curving mean water surface caused by wave setup.

Wave characteristics were extracted using both spectral and zero-crossing approaches. Both approaches generally show good agreement with the buoy data (see Table 1). Considering the depth and offshore distance where wave rider buoy is located (1200m offshore and 18m depth) and also the fact that the waves are subjected to transformation process (e.g. refraction, shoaling) while they travel between the buoy and the tubes, it is expected that some differences between the tube and buoy data sets will exist. The comparison between the Gold Coast Buoy and tube system for different time-block data is shown in Table 1. Significant wave height (H_s) and maximum wave height (H_{max}) are derived from the zero-crossing method and the represented peak period (T_p) in right hand side of Table 1 obtained from Spectral method to show the general conformity of both methods with Buoy data.

Table 1. Wave characteristics of Gold Coast Buoy against Manometer Tube System

Tube Length Time-Block	H_{sign} (Zero-up)					H_{max} (Zero-up)					T_p (Spectral)				
	400	300	250	200	GCB	400	300	250	200	GCB	400	300	250	200	GCB
9:00 AM	0.87	1.1	1.36	1.1	1.05	1.44	1.64	1.91	1.62	1.8	8.03	7.95	7.95	8.03	8.33
9:30 AM	0.92	1.16	1.42	1.18	1.09	1.49	1.77	2.04	1.82	1.66	7.55	7.55	7.66	7.66	8.33
10:00AM	0.89	1.12	1.42	1.21	1.11	1.27	1.77	2.46	1.89	2	7.95	7.31	7.52	7.25	8.33
10:30AM	0.92	1.15	1.3	1.14	1.09	1.32	2.05	1.95	1.83	1.56	7.84	7.88	7.84	7.73	8.33
11:00AM	0.95	1.18	1.38	1.17	1.01	1.34	1.95	2.28	1.99	1.77	8.03	7.99	7.95	8.07	7.69
11:30AM	0.89	1.08	1.32	1.16	1.08	1.44	1.64	2.16	1.85	1.74	7.76	7.76	7.8	7.76	8.33
12:00PM	0.96	1.15	1.36	1.15	1.08	1.29	1.75	2.07	1.83	1.77	5.85	5.77	5.65	5.77	8.33

DATA ANALYSIS AND DISCUSSION

All continuous data break in to 30 min block to make consistency with Gold Coast wave rider buoy. Figure 5 and Figure 6 represent the spectral and zero crossing analysis of the first block of TC Hamish data respectively.

Figure 4. Verifying water level against Maritime Safety Gauge data

Figure 5. 500m tube Energy Density Spectrum, in first 30min block of data

Table 2. General conditions of each event (BoM (2009); DERM (2009))

Event	Date	Record Duration	Max Wind Speed	Wind Direction	H _{sign}	H _{max}	Damage to Beaches
Tropical Cyclone Hamish	March 2009	3 Days	215 km/hr	East to Northeast	4.7m	8.4m	Moderate erosion
East Coast Lows	May 2009	1 Day	117 km/hr	East to Southeast	6.2m	10.6m	Significant erosion

Figure 6. Part of time series data for 500m tube in first 30min block of data

General Observations

General conditions experienced in the two stormy events are presented in Table 2. Also, Figure 7 provides some example data of the significant wave height profile for each of the events which indicates that the offshore wave height in the ECL was larger than TC Hamish. Moreover, Figure 7 shows that the rate of energy dissipation in ECL is higher than TC Hamish (i.e. in ECL 3m offshore wave height reaches 0.5m near shoreline, however, in Hamish it changes from 2m offshore wave to 1.4m nearshore), which the surfzone bathymetry can explain the differences (see Figure 8). Inspection of Figure 7 indicates the presence of two breakpoints, an offshore and nearshore breaker line, at approximately 400m and 160m respectively.

Figure 7. Wave height of first two blocks of each events

Beach Profiles

Beach profile differences are illustrated in Figure 8. Comparing the beach profile before and after Hamish, there were no considerable changes in the profile. A small amount of erosion occurred in swash zone at about 50m, and also the offshore bar moved about 50m offshore as it can be seen in Figure 8. However, the ECL event caused massive changes in beach profile. Enormous amount of sands was eroded from the beach dunes and consequently the beach profile became much flattened in next 80m after shoreline.

Table 3. Surf similarity parameter for each events

Offshore distance of breaker line		400 (m)	160 (m)	Throughout Surfzone
TC Hamish	Local Surf Similarity ξ	0.149	0.113	0.141
ECL	Local Surf Similarity ξ	0.243	0.231	0.265

Surf Similarity Parameter

Considering the beach profiles (Figure 8) and the result of wave analysis, the surf similarity parameter (ξ) corresponding to each event is provided in Table 3. During TC Hamish ξ was about 0.141, however, it increases about 90% in ECL which is 0.265. According to CEM (2002) and considering these values, dominant type of breaking expected to be spilling however visual observations during both events saw a significant proportion of plunging type breakers. Hence, CEM (2002) criteria for defining the breaker type doesn't seems accurate enough for defining the in breaker type in The Spit under these two stormy events.

Figure 8. Beach profile changes

Wave height to water depth ratio, γ

The present data has been used to test the ability of existing expressions from the literature to predict the behaviour of γ_s , the ratio of significant wave height to water depth. Thornton and Guza (1983) measured wave transformation at Torrey Pines Beach, California, during November 1978. Sensors located along an on-offshore transect from 10m depth to the inner surf zone. This measurement conducted in calm situation which the offshore wave height varied between 0.6m to 1.6m and the average peak frequency of the incident wave spectra varied little during the experiments and was about 0.07 Hz. There was no stormy wave recorded. Based on their observation they suggested that γ_s is about 0.6 (see Figure 9).

Sallenger and Holman (1985) based on collected data during storm, $1.96 < H_o < 2.4$; $6.9 < T_p < 16.8$, said that γ_s is related to beach profile (i.e. $\gamma_{rms} = 3.2 \tan \beta + 0.3$). in the other hand, Combining low and high wave steepness data collected on barred and unbarred beaches in the laboratory and field, Nairn (1990) suggested that γ_s increases with increasing offshore wave steepness. The data used by Nairn (1990) were collected in the Grossen Wellenkanal (Big Wave Flume) at Oranjemund in Namibia and during hurricane Eloise on the Florida coast. H_{rms} and peak period vary between 1m to 2.6m and 6s to 14s respectively. However, these data were collected just in inner surfzone area.

Vincent (1985) presented laboratory and field observations in which the significant wave height was proportional to $\gamma_s \propto h^{-1/2}$ in the outer surf zone but γ_s was approximately constant in the inner surf zone. Field data used by Vincent (1985) were collected during storm on October 25, 1980 in which significant wave height reach 5m in 36m depth buoy. He studied collected data in six different points from relatively depth water (36m) to shallow water (2.7m). However, Vincent did not proposed specific formulation purely for storm condition in his work.

As illustrated in Figure 9, Thornton and Guza (1983) doesn't show good agreement with the present data. Moreover, Nairn (1990) expression doesn't agree with the data at all which is γ_s increases with increasing offshore wave steepness. However, Sallenger and Holman (1985) expression has a good agreement with the offshore data but still doesn't satisfy the inner surfzone. Vincent (1985) qualitatively predicts the trend of increasing γ_s with decreasing depth. However, Vincent (1985) expression needs to be modified since the recorded γ_s values first, haven't shown constant values in inner surf zone and second, variation range of this expression hardly covers all the γ_s values extracted from field data. In addition in outer surf zone, it isn't delicate enough to mention that $\gamma_s \propto h^{-1/2}$.

Figure 9. Comparison of existing model against collected data

Field data mentioned in both Figure 9 and Figure 10 include two different stormy events (i.e. TC Hamish, ECL) as well as calm condition one. Therefore, this data scatter is elaborate enough to cover almost all the wave conditions in this area.

Figure 10. Curve fitting for extracting more accurate relation for γ_s

In order to develop an accurate model of energy dissipation based on actual field data, it is essential to represent γ_s as simple and accurate as possible. By drawing the envelopes of data (see Figure 10) and extracting the equation of average amount of envelopes the following empirical equation for γ_s is suggested:

$$\gamma_s = \pi^2 \left(\frac{4.6 - h^{1.1} \times \ln(h)}{70h^{1.1}} \right) + 0.46 \quad (8)$$

where, h is water depth.

CONCLUSION

Analysis and comparison of stormy wave data from two severe storms which hit the South-east coast of Queensland in 2009 have provided an opportunity to test the performance of existing predictors of the behaviour of γ_s against storm data. The result of this paper indicates that, the existing expressions for the experimental wave height to water depth ratio, γ_s , don't reflect exactly what happened while storm wave trains travel from offshore toward inner surf zone. Study two severe events plus calm condition data reveals that the exponential function is the best fitting formula for γ_s changes against water depth throughout the surfzone. Moreover, Current criteria of breaking type in existing literatures doesn't describe the breaker type under storm condition at all.

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