An Investigation of wave impact pressures on an offshore wind turbine substructure subjected to breaking focused waves

Vijaya Kumar Govindasamy
Department of Ocean Engineering
IIT Madras
Chennai, India
gvijayakumaraero@gmail.com

Mayilvahanan Alagan Chella
Department of Civil and Environmental Engineering
NTNU
Trondheim, Norway
m.vahanan@gmail.com

Panneer Selvam Rajamanikkam
Department of Ocean Engineering
IIT Madras
Chennai, India
pselvam@iitm.ac.in

Vipin CP
Department of Ocean Engineering
IIT Madras
Chennai, India
vipincp.iitm@gmail.com

***Abstract*— Offshore Wind Turbines (OWT) are very attractive candidates for renewable energy production for several obvious reasons such as stronger wind speeds and cleaner energy production. Among the two variants of the OWT's, namely, fixed and floating configurations, the former can be considered as an optimal solution considering the trade-off between factors such as economics, proximity to land and efficiency. The motivation is to get a deeper understanding of the interaction of breaking focused waves with a bottom fixed vertical cylinder by performing lab experiments. In shallow waters, one of the primary factors governs the design of a fixed OWT substructure is hydrodynamic loads acting on it due to breaking waves. The main objective of the study is to investigate wave impact pressures on a monopile substructure subjected to breaking focused waves. Laboratory experiments are conducted in a 30m long, 2m wide and 1.8m deep wave flume, at Department of Ocean Engineering, Indian Institute of Technology Madras, India. The generation of breaking focused waves is accomplished by linear superposition of wave components. Following the simulation procedure, the desired signal to the wave maker was computed by combining 28 sinusoidal wave components within the frequency range from 0.42Hz to 1.10Hz. The cylinder model is made of acrylic material of 0.2m diameter, 0.005m thickness and length of 1.3m. The cylinder is placed at the center of 2m wide flume. The wave induced dynamic pressures were measured at eight different positions along the depth of the vertical cylinder for different intensities of plunging breaking waves by using pressure transducers . The pressure transducers are connected along the front line of the cylinder facing the wave. There are six pressure transducers positioned above the Still Water Level (SWL). Then, the seventh transducer and the eighth transducers are positioned at and below SWL. The top six pressure transducers are uniformly spaced at an interval of 0.04m and the last two transducers are spaced at an interval of 0.06m. The pressure measurements are recorded in the front of the cylinder in order to investigate the wave induced impact pressure on the monopile due to breaking focused wave. The kinematics, breaking characteristics, focused wave surface elevation, pressure-time profile, pressure rise time, vertical pressure profile, are measured for four different incident wave characteristics and environmental conditions.**

Keywords— offshore wind turbines; breaking focused waves; wave interaction; wave focusing; impact pressure; pressure rise time;

I. INTRODUCTION

Offshore Wind Turbines (OWT) are very attractive candidates for renewable energy production for several obvious reasons such as stronger wind speeds and cleaner energy production. Among the two variants of the OWT's, namely, fixed and floating configurations, the former can be considered as an optimal solution considering the trade-off between factors such as economics, proximity to land and efficiency. Around the world, most of the coastal and offshore structures are constructed by using slender cylindrical member as the fundamental component. Similar cylindrical members are used in the offshore industry as bottom supported structure for oil and gas production especially in shallow water. For coastal and offshore engineers, in addition to regular wave action for wave-interaction analysis, the wave action also consists of irregular, asymmetric and extreme waves including breaking waves. Breaking wave loads are significantly important for all coastal structures Thus, one of the primary factors that govern the design of a fixed OWT substructure in shallow water is the wave loads acting on it due to breaking waves. Focused waves are characterized as single, remarkably horizontally asymmetric and extremely high waves, which have an unpredictable nature and can appear unexpectedly even in relatively calm sea state. This is not only occurring in deep water but also occurring in shallow water depth, for instance the extreme high waves recorded near the Cape Olga, Kamchatka (Russia). These waves will lead to damages to ships, offshore and coastal structures if not considered properly in the analysis of structure. One of these reasons is wave-wave interaction. The wave focusing technique can be used to generate extreme wave events in the laboratory.

Although the occurrence of focused waves has been widely acknowledged, these waves occur in such a short period of time that only a few measurements of these waves in nature are available. The design of reliable and economic OWT's and offshore structures requires further knowledge of the interaction of focused waves with structures. It is therefore important that concerted efforts are implemented to provide detailed measurements and analysis. The occurrence of focused waves is ascribed to four different processes: wave-current interactions, wave-bottom interactions, wave-wave interactions and wind-wave interactions.

The pioneering work of generation of breaking focused waves based on nonlinear wave-wave interaction was first proposed by Longuet-Higgins (1974) [1]. In this method, a specified range of wave components (primary components) are generated and their phases are adjusted in such a way that at a certain point in time, the individual wave components are focused at a specified location. Thus, a large wave height occurs due to superposition of wave components. This method of nonlinear wave-wave interaction has been used for breaking wave generation experimentally by Rapp and Melville (1990) [2]. Wienke and Owmeraci (2005) [3] conducted a series of large scale model experiments to investigate wave impact loads on vertical and inclined slender cylinders for five different loading cases by using Gaussian wave packets. They showed that the impact force strongly depends on the distance between the breaking location and the cylinder. Baldock et al (1996) [4] conducted a laboratory study of nonlinear surface waves on water, and showed that the nonlinear interaction of the different components will produce significant increase in both crest elevation as well as the underlying kinematics. Fernandez et al. (2014) [5] proposed a self-correcting method for generating breaking and non-breaking focused waves for both constant as well as variable water depth. Manjula et al (2013) [6] discussed the hydrodynamic response of a top fixed vertical cylinder due to breaking wave impact. Mayilvahanan et al (2016) [7] investigated on hydrodynamic characteristics and geometric properties of plunging and spilling breakers over impermeable slopes. Recently Hans bihs et al (2017) [8] analyzed the interaction of focused waves with a vertical cylinder using REEF3D. However, the estimation of regular breaking wave loads for bottom fixed slender cylinders exists in literature, whereas the focused breaking wave load on cylinder structure requires a lot more study. This forms the motivation of carrying out a experimental investigation in this aspect and this paper focuses on the details of experiments conducted to measure wave impact pressures and breaking wave profile on a fixed OWT substructure subjected to breaking focused waves.

II. EXPERIMENTAL SETUP

Experiments are conducted in a well-controlled programmable wave generation facility, 30m long, 2m wide and 1.8m deep wave flume, at Department of Ocean Engineering, Indian Institute of Technology Madras, India. The sectional view of the wave flume is shown in Fig. 1. The wave flume has a piston type wave maker at the one end and a rubble mound wave absorber at the other end. The wave absorber is used to absorb the incoming waves in order to avoid the wave reflection from the rear end of the flume. The experimental setup consists of a horizontal bed portion with a water depth of 0.8m, see Fig. 2. The generation of focused breaking focused waves is accomplished by linear superposition of wave components (Chan and Melville, 1988) [9]. Following the simulation procedure, the desired signal to the wave maker was computed by combining 28 sinusoidal wave components within the frequency range from 0.42Hz to 1.10Hz. Details of the generated focused wave group are given in TABLE 1.

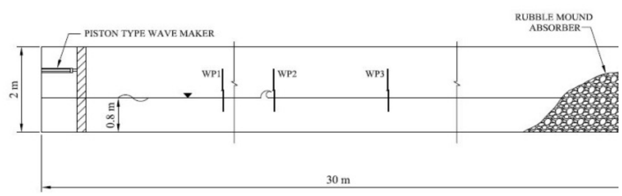

Fig. 1. Sectional view of wave flume with wave probes

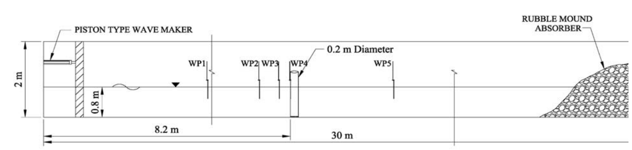

Fig. 2. Sectional view of experimental setup for cylinder with horizontal sea bed

TABLE 1. Input parameters for the generation of wave packet

Parameters	**Value**
Initial frequency	0.42
Final frequency	1.1
Centre frequency	0.76
Frequency bandwidth	0.895
Number of wave components	28
Characteristic wave period	1.32
Characteristiv wave length	2.7
Wave number corresponding to center frequency	2.327
Characteristic wave speed	2.053

III. DETAILS OF VERTICAL CYLINDER MODEL

The cylinder model is made of acrylic material of 0.2m diameter, 0.005m thickness and length of 1.3m. The cylinder is placed at the center of 2m wide flume and it is fixed firmly to the flume bottom by using the rigid frame. The top side of the model is kept free. The cylinder joints are completely sealed to make it a water tight unit. The pressure measurements are obtained simultaneously using 0.2bar kistler transducers. The pressure transducers are connected along the front line of the cylinder facing the wave. The wave induced dynamic pressures are measured at different elevation such as above and below SWL along the depth of the bottom fixed vertical cylinder under four different intensities of plunging breaking waves by using eight pressure transducers. There are six pressure transducers positioned above the SWL. Then, the seventh transducer and the eighth transducers are positioned at and below SWL. The top six pressure transducers are uniformly spaced at an interval of 0.04m and the last two transducers are spaced at an interval of 0.06m. The position of the pressure transducers on the front face of the vertical cylinder is shown in Fig. 3.

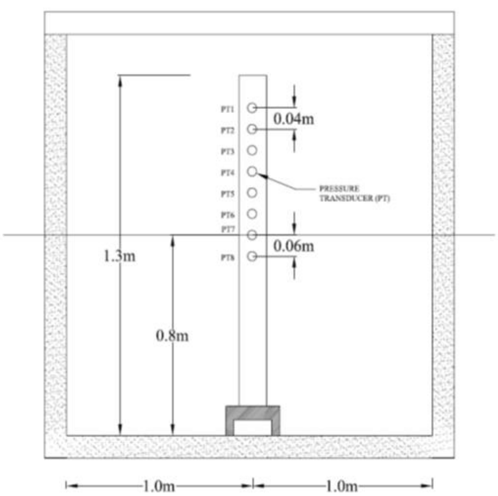

Fig. 3. Sectional view of cylinder with pressure transducers

IV. BREAKING WAVE CHARACTERISTICS

The breaking focused waves are simulated in a constant water depth of 0.8m based on constant steepness wave packet (CS) (Lekshmi, 2008 [10]). For each run, the cylinder was first secured rigidly on the bottom at a predefined focused location within the wave breaking zone. On the completion of each run, the tank is allowed to settle down before carrying out the next run. The obtained input time series of free surface elevation from the constant steepness wave packet is shown in Fig. 4. In the present experiments, the measurements are recorded at the fixed cylinder location (8.2m from the wave maker) for four different intensities of focused plunging waves. Different intensities of plunging breakers are achieved by adjusting the gain (tuning) factor. The tuning factor influences the overall energy level in the generated wave packet and thus it controls the intensities of wave breaking. The tuning factors obtained for different intensities of plunging breakers and, their wave steepness parameters and the measured breaking wave heights (H_b) are given in Table 2. The maximum tuning factor corresponds to a strong plunging (P4) breaker. The free surface elevation is measured by using the wave probes at the focus point for four different focused plunging breaker cases such as weak (P1), moderate (P2), fine (P3) and strong (P4) plunging wave cases and are plotted in Fig. 5(a, b, c and d) respectively.

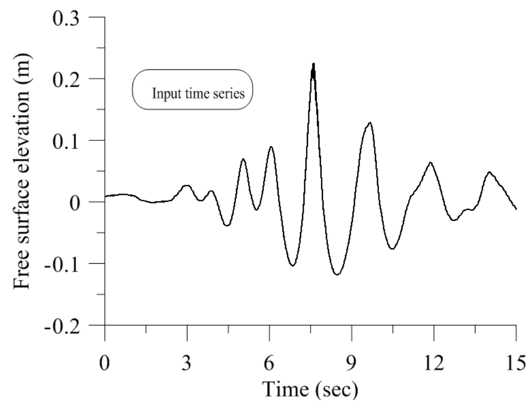

Fig. 4. Input time series to wave maker for constant steepness wave packet

TABLE 2. Gain factor (G), Wave steepness parameter (γ) and Breaking wave height (H_b)

Types of breaking	**Gain factor (G)**	**Wave Steepness parameter**	**Breaking wave height (m)**
Weak Plunging (P1)	0.66	0.292	0.3894
Moderate Plunging (P2)	0.68	0.301	0.3962
Fine Plunging (P3)	0.70	0.310	0.4007
Strong Plunging (P4)	0.72	0.319	0.4012

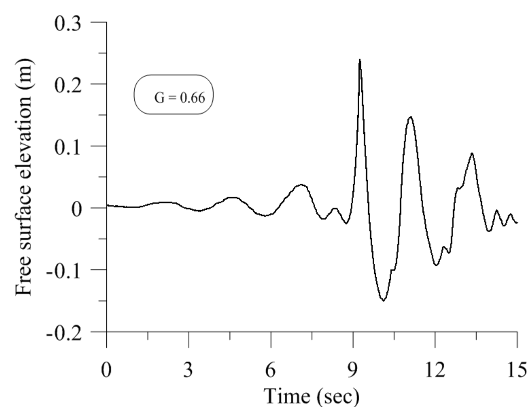

Fig. 5a. Free surface elevation at focus point for P1

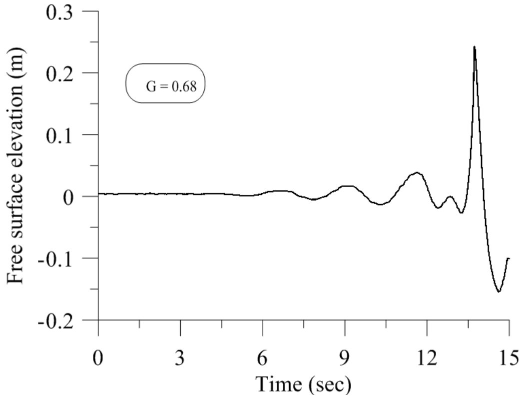

Fig. 5b. Free surface elevation at focus point for P2

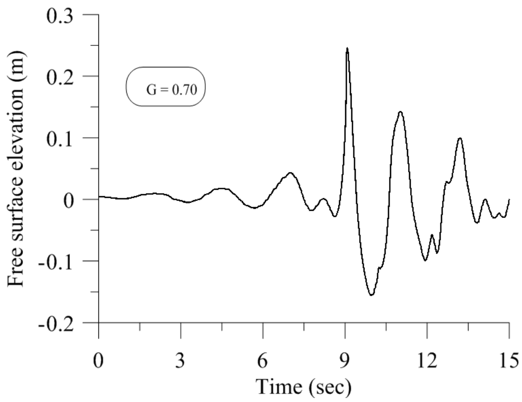

Fig. 5c. Free surface elevation at focus point for P3

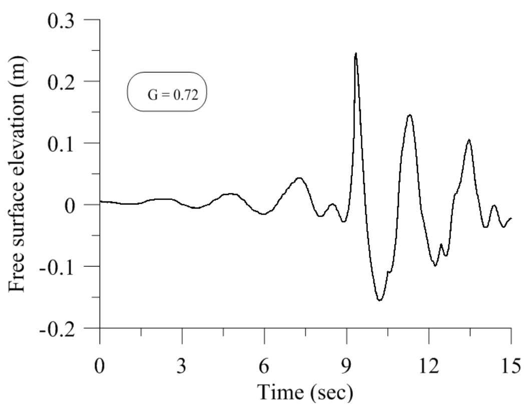

Fig. 5d. Free surface elevation at focus point for P4

V. RESULTS AND DISCUSSION

A. Pressure distributions and characteristics

The variation of the normalized pressure-time history for four different focused plunging cases (P1, P2, P3 and P4) at various elevations (Z/H_b) along the front face of the cylinder is shown in Fig. 6 (see, next page). The measured pressures were normalized by ρC^2, where ρ is the water density ($1000 kg/m^3$) and C is the characteristic wave speed of the generated wave packet. The relative time (t*) and the vertical elevations were normalized by $(t-t_b)/T_c$ and (Z/H_b), where t_b is the focusing time, T_c is characteristic period corresponding to the center frequency, and H_b is the measured breaking wave height at the focus point. It can be seen from the pressure records that, at predefined focused location the pressures are characterized by an impact region, where the pressures maxima are high (>3 ρC^2). These pressures subsequently referred to as the impact pressures, are also characterized by small oscillations immediately following the peak pressure especially in the region of SWL. Among four plunging breaker cases, the largest impact pressure occurs for case 4 ($P_{imp}/\rho C^2 = 8.98$) which is at 0.26m ($Z/H_b = 0.64$) above from the SWL while the cylinder was kept at 8.2m from the wave maker (focus location). This observation of the maximum impact is consistent with the experimental studies by Chan et al (1995) [11] and Manjula et al (2013) [6]. The maximum impact pressure observed for fine plunging (P3) wave is 5.86 which is almost equal to the measured impact pressure at SWL. Comparison of impact pressure for four different plunging cases at 0.26m from the SWL ($Z/H_b = 0.64$) is shown in Fig. 7.

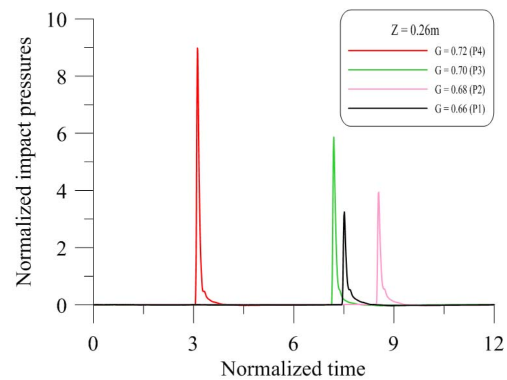

Fig. 7. Comparison of normalized pressures at Z = 0.26m ($Z/H_b = 0.64$) from SWL for four different plunging cases

But in the case of moderate (P2) and weak plunging (P1) wave conditions, the maximum impact pressure is observed at the SWL as compared to cases P3 and P4. Comparison of impact pressure for four different plunging cases at SWL ($Z/H_b = 0$) is shown in Fig. 8.

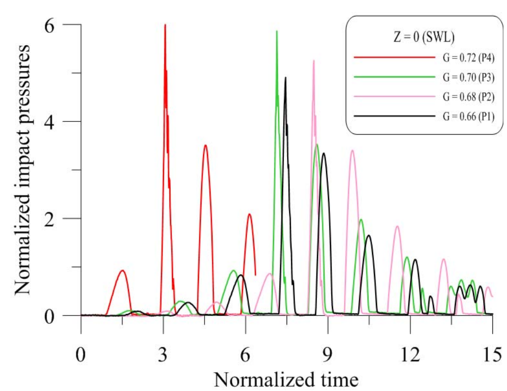

Fig. 8. Comparison of normalized pressures at SWL ($Z/H_b = 0$) for four different plunging cases

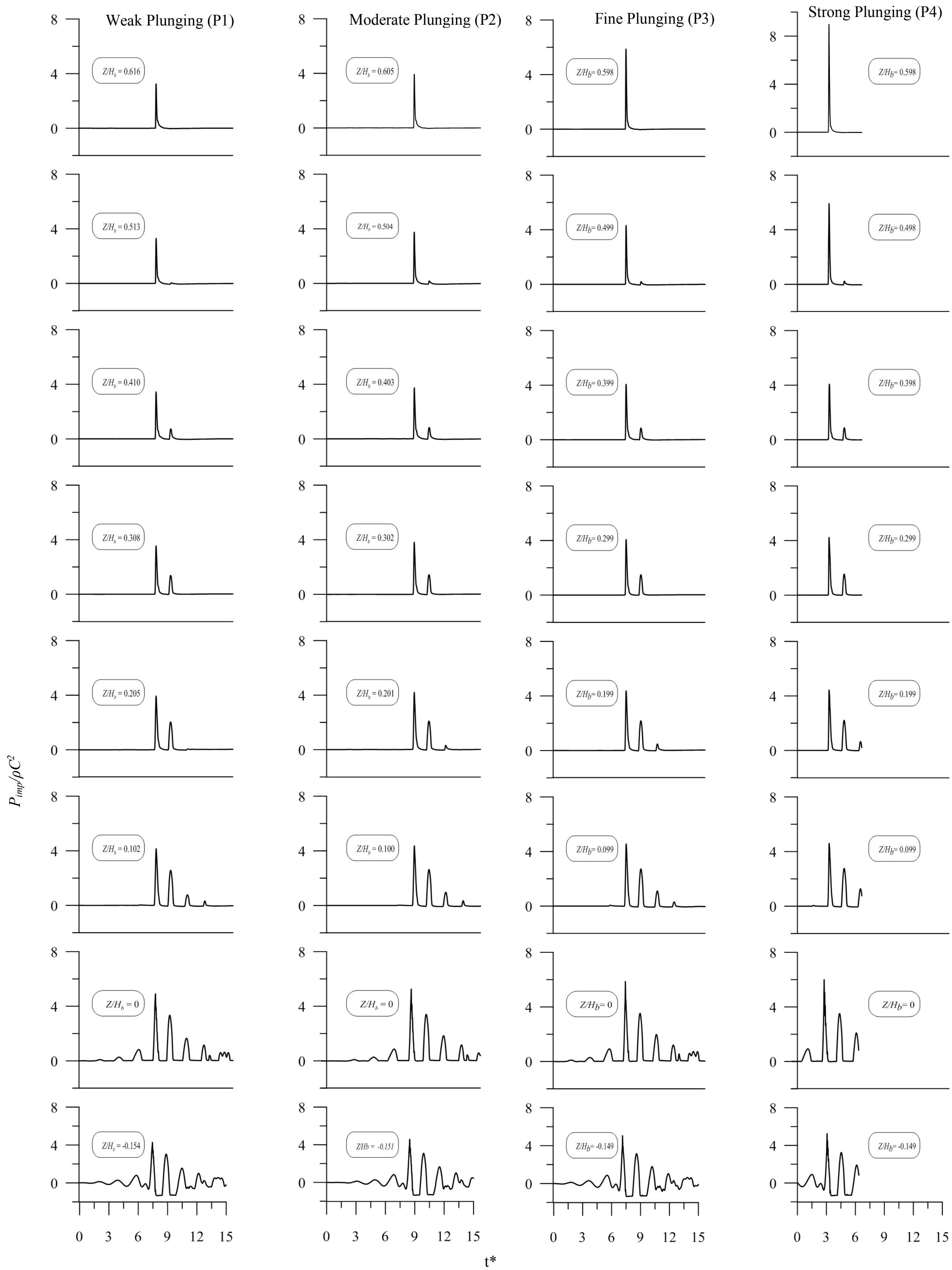

Fig. 6. Temporal variation of normalized pressure time history at elevations along the front case of the cylinder for four different plunging cases

B. *Pressure rise time*

The pressure rise time is defined as the time difference between the point at the pressure starts to increase/rise to the point of peak pressure. It plays a major role in describing the magnitude of impact pressure and the resulting impulse. The pressure rise time profile for case P4 is shown in Fig. 9.

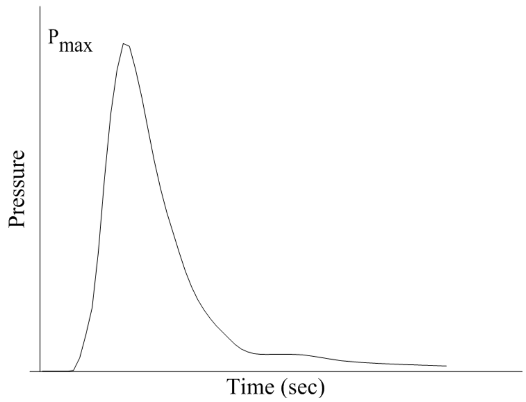

Fig. 9. Pressure rise time profile for P4 plunging case

The calculated pressure rise time and the maximum impact pressure for four different plunging cases are listed in Table 3. In the present study, the normalized impact pressure ($P_{imp}/\rho g H_b$) is 9.62 for the strong plunging (P4) case corresponding to the measured maximum breaking wave height (H_b) of 0.4012m. This observation is similar to the findings reported by Rajasekaran et al (2010) [12] who investigated impact pressures on a vertical wall under similar laboratory conditions.

TABLE 3. Pressure rise time and maximum impact pressure for four different plunging cases

Types of breaking	**Pressure rise time (sec)**		**Maximum impact pressure ($P_{imp}/\rho C^2$)**	
	***Z* = 0**	***Z* = 0.26m**	***Z* = 0**	***Z* = 0.26m**
Weak Plunging (P1)	0.32	0.1	4.9081	3.2469
Moderate Plunging (P2)	0.32	0.12	5.2574	3.9372
Fine Plunging (P3)	0.26	0.18	5.8640	5.8655
Strong Plunging (P4)	0.24	0.09	5.9973	8.9811

The maximum breaking wave induced impact pressures from different experimental studies are given in Table 4. The distribution of induced pressure along the elevation of cylinder under the four different plunging cases is shown in Fig. 10. The maximum impact pressure occurs for case P4 at an elevation of $0.65H_b$ above SWL. The variation of maximum impact pressure for four different wave steepness parameters is shown in Fig. 11. From the Fig. 11, it is observed that maximum impact pressure increases as the wave steepness increases.

TABLE 4. Maximum breaking wave induced impact pressure on the cylinder and vertical wall

Structure		**$P_{imp}/\rho g H_b$**
Slender cylinder	Present study	9.62
	Manjula et al (2013)	16.7
	Oumeraci et al (2005)	69.5
Vertical wall	Rajasekaran et al (2010)	13.5

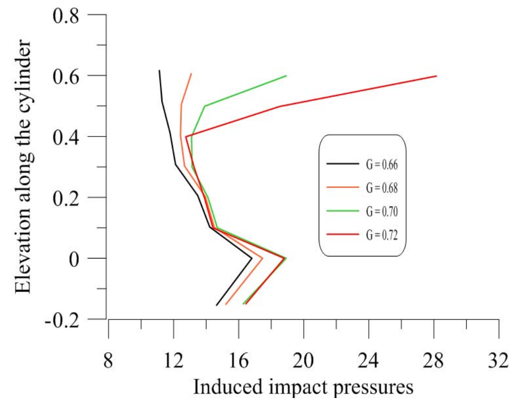

Fig. 10. Variation of induced impact pressure along the elevation of cylinder for four different plunging cases

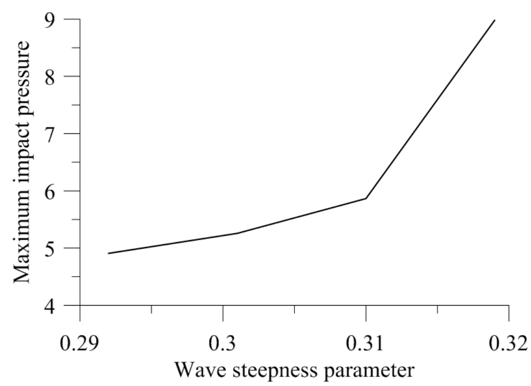

Fig. 11. Variation of maximum impact pressure for four different wave steepness parameters

VI. CONCLUSION

An experimental investigation on breaking focused wave impact on a bottom fixed vertical slender cylinder has been carried out for four different intensities of plunging breaking waves under constant steepness spectrum. Breaking waves were generated in laboratory using the principle of energy focusing by linear superposition of wave components. The water surface elevation, wave induced impact pressure and corresponding pressure rise time were measured on the simulated wave packet. Based on the measurements the following conclusions can be drawn. The largest wave impact pressure (8.98) occurs for strong plunging case at 0.26m above the SWL while the cylinder was kept at the focused location (8.2m from the wavemaker). The pressure rise time for this case is 0.09s. In the future work, the experimental measurements will be compared against the Numerical model (REEF3D), to provide a combined experimental–numerical methodology for predicting focused breaking wave forces on a monopile.

ACKNOWLEDGMENT

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