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Wave impact load on jacket structure in intermediate water depth

C. Sruthi, V. Sriram*

Department of Ocean Engineering, Indian Institute of Technology, Madras, India

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ABSTRACT

The aim of this study is to estimate impact forces on a jacket using the improvised methodology and to propose a slamming coefficient for the jacket structures. Four types of structures have been discussed in this study, single cylinder (SC), legs with connecting braces in wave direction, legs with connecting braces transverse to wave direction and jacket structure. The SC case was analyzed using the improvised methodology and the obtained slamming coefficient was validated with the existing literature. Based on this initial validation, the methodology was extended for other models. Four loading cases were identified based on the location of the wave breaking. The impact load estimated was compared with theoretical formulas given by Goda et al. (1966), Wienke and Oumeraci (2005) for all models. The slamming coefficient (Cs) was found for wave characteristics having spectral bandwidth ratios of 1 and 0.75. For both the wave characteristics, the Cs was found to be higher for the loading case, when the wave breaks in front of the structure. The Cs varies between 2.2 and 4.6 depending upon the wave characteristics, with maximum obtained for 0.75. The method used in this paper can be used for estimating impact loads on complex structures.

1. Introduction

The jackets have to be built in order to withstand the harsh sea environment. Such designs demand in-depth analysis to predict the loads acting on the structure. Wave impact loading on the ocean structure is a very important problem as it may cause failure in the structure if the breaking wave loads were not considered properly in the analysis of the structure. There were a lot of empirical relations proposed to find the loads due to breaking waves. The breaking wave load acts for a very short period of time and the magnitude of the load is high. When the waves break on the structure, the members are subjected to very high loads. Especially the members near the sea surface suffer loads higher in magnitude, as they submerge first when the wave breaks on the structure. These higher loads can cause additional stresses in local members and there is a possibility for collapse. Further, as the impact is rapid, the dynamic effect of the load will be high, which needs to be investigated. Most of the works are carried out with the simplified structure such as a cylinder, as it is widely used in the offshore industry. To find an alternate source of energy, researchers are working in wind, wave, tidal energy and its hybrid systems in the ocean. The difference between the offshore platform support structure and the offshore wind energy support structure is that the latter has a long tower with a nacelle at the top, thus the dynamics are different for the wave impact loads as its frequency may fall near the natural frequency of the structure. Hence, a clear understanding is required. Further, most of the wave impact loads were carried out either in the deep water region for offshore platform or in the shallow water region for coastal structures. In order to account for the breaking load, the concept of introducing the additional term in Morison Equation (Morison et al., 1950) was proposed to estimate the total load. Hence, the total force is given by

$$F = F_D + F_I + F_S \quad (1)$$

Where F_D is the drag component of force which depends on the nonlinear function of the velocity and the second term F_I is an inertia component which depends on the linear function of acceleration. In order to account for breaking load, additional drag term, Fs which depends on the impact velocity with slamming coefficient (Cs) was introduced. To obtain the impact force on the structure, Goda et al. (1966) used the mathematical model of the water entry problem (Von Karman, 1929) to calculate the impact force of a breaking wave on a slender cylinder.

$$F(t) = \lambda.\ \eta.\ \pi.R.C^2(1 - C.t/R) \quad (2)$$

In the above equation, R is the radius of the cylinder, η is the maximum elevation at the breaking location and C is the celerity of the wave which can be considered as horizontal water particle velocity of the wave when it is breaking. The curling factor λ is given as 0.07–0.46 by Goda et al. (1966) which is the portion of η which hits the structure while plunging. Campbell and Weunberg (1980) conducted experi-

* Corresponding author.
E-mail addresses: vsriram@iitm.ac.in, send2sriram@gmail.com (V. Sriram).

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ments with horizontal cylinder penetrating through the water surface and estimated that the maximum slamming coefficient at the time of initial contact with water wave as 5.15, which was recommended by DNV-RP-C205 (2010)

In order to understand the dynamic nature of the structure for varying wave impact energy, different types of breaking wave were also investigated (Sawaragi and Nochino, 1984). The comparison was made between measured maximum forces and estimated by Goda et al. (1966). For spilling breaker, the slamming coefficient was found to be same as that of Goda et al. (1966). For plunging breakers, the calculated slamming coefficient was found to be 9. The study also mentioned that there was a clear rise time before the peak force instead of sudden onset of peak force at time t=0, as pointed out by Goda et al. (1966). In order to understand the impact load for different stages of breaking process and to know the influence of breaking position, Chan et al. (1995) carried out an experimental investigation on cylinder subjected to wave breaking. The study has discussed the influence of impact force on the cylinder.

In contrast to the mathematical model proposed by Von Karman (1929), Wagner (1932) considered the pile-up effect around the cylinder. Due to this pile-up effect the cylinder immersion is quick and the force increases. The maximum line force is given by

$$F(t) = 2.\ \pi.\ R.\ V^2 \tag{3}$$

Wienke (2001) used Wagner theory and maximum impact force is given by

$$F(t) = \lambda.\ \eta.\ 2.\ \pi.\ R.\ C^2 \tag{4}$$

They proposed a methodology based on Duhamel Integral to estimate the impact force and also generated different loading cases as carried out by Chan et al. (1995). The non-breaking load was subtracted from the measured breaking load to obtain the dynamic load due to wave breaking. The curling factor was obtained by equating the obtained impact force from the method they used and the theoretical impact force calculated from the model proposed by Wagner (1932). The distinct feature of this work is that the experiments were carried out in large scale when compared to Goda et al. (1966) experiments. The impact load predicted by Wienke and Oumeraci (2005) is twice the force given by Goda et al. (1966) and the impact time is much less than the time of impact proposed by Goda et al. (1966). This may be attributed to the scale effects.

Recently, Hildebrandt (2013) has carried out large-scale investigation on the cylinder with tripod legs. The experimental results such as wave elevation and pressure were initially compared with a numerical model based on weakly coupled approach (Hildebrandt and Sriram, 2014) by combining Fully nonlinear potential flow solver (Sriram et al., 2015) and ANSYS-CFX and the impact forces were estimated numerically. It was concluded that the impact load was similar to the theoretical impact force proposed by Goda et al. (1966) and the load was not high as predicted by Wienke and Oumeraci (2005), whereas rise time is as same as given by Wienke and Oumeraci (2005).

Breaking solitary waves on a single cylinder has been studied by Alagan Chella et al. (2016), Mo et al. (2013) and vertical wall studied by Cuomo et al. (2010). In reality, not only monopile structures are used, but also jacket structures are widely employed as support structures. The breaking load on the jacket structure recently gained attention due to offshore wind energy support structures in shallow water as they can experience the dynamic action. An extreme event, 15 m wave height in a short duration was recorded at FINO 1 platform in the North Sea, Germany (Fig. 1). The time duration for this 15 m high breaking was only 10 s as shown in the figure.

Aashamar (2012) estimated the impact force acting on a jacket through frequency domain analysis, which was originally used by Määttänen (1979) to resolve ice forces from measured response forces on structures subjected to moving ice. In their methodology, *H(ω)* is the frequency response function (FRF) and *SF(ω)* is the linear spectrum of the applied force. An impulse hammer was used to estimate the FRF. The structure was hit by the impulse hammer in several places, which may possibly come in contact with the breaking wave. The inverse fast Fourier transform (IFFT) of S(ω)/H(ω) gives the high frequency components. The high frequency components has been filtered by a low-pass filter, to obtain a force time series in order to obtain the wave slamming force.

Recently, Yin Tu et al. (2016) carried out experiments in large scale (1:8) on a truss structure and calculated impact force using conjugate gradient technique and linear regression with the least square technique. The techniques have been applied to the measured local forces from the transducers. Hammer tests have been conducted and have been used in the above analysis.

In API RP 2A (2000), to find slam forces, the coefficient C_s lie between 0.5 and 1.7 times the theoretical value of π, depending on the rise time and natural frequency of the elastically mounted cylinder. Sarpkaya (1978) recommend that if a dynamic response analysis is performed, the theoretical value of C_s to be taken as π; otherwise, a value of 5.5 should be used as slamming coefficient. According to DNV-RP-C205 (2010), at the initial time of impact, C_s (0) is taken as 5.15. The above model is a good approximation when the impacting wave is steep. When the cylinder is fully submerged, C_s has to be considered as 0.8. According to CERC (1984), C_s is 2.5 times that of Drag Coefficient (C_d). Since the Reynolds number generally will be in the supercritical region (C_d=0.7), for breaking wave forces C_d of 1.75 is recommended.

In the above literature, different methods have been proposed to estimate impact force from experiments. There are lots of differences in slamming coefficient value for the experiments conducted on a single cylinder. Very few experiments were conducted on the truss structure and these studies ascertain the fact that the load is going to be different from that of a cylinder. Even with experiments conducted on the jacket, it is very difficult to give a physical explanation of what is happening in a jacket when breaking wave acts, as there are numerous members in a jacket which is going to interact with the breaking wave. Hence, in this paper an attempt has been made to address the problem by conducting experiments on individual braced structures to give more information on the whole jacket.

Further, the methodology to arrive at the impact force is also not clear. Different methodologies have been adopted by researchers to estimate the impact force on the truss structure (Aashamer, 2012; Tu et al., 2016). In Frequency domain analysis, the knowledge of cut-off frequency to filter off the quasi-static part becomes very difficult. When a low-pass filter is used, few components which are required for the analysis could be filtered. This may lead to a reduction in estimation of impact force in frequency domain analysis. Hence, time domain analysis based on Duhamel integral may be considered as an alternative approach, which is attempted in this study. In this paper, we have used the method proposed by Wienke and Oumeraci (2005) with improvements to obtain the impact force on the jacket. The main argument for preferring Wienke and Oumeraci (2005) methodology is that hammer response (as in Aashamer (2012)and Tu et al. (2016)) cannot replicate the actual impact of the wave. The randomness in wave load is found to be very high and the wave does hit the structure at an instantaneous time like a hammer. Hence, after estimating the impact force, the total response was calculated from the estimated impact force and was compared with the measured total response as carried out by Wienke and Oumeraci (2005). This process will ensure the correctness of the estimated magnitude of impact force.

The paper is arranged as follows. The experimental setup is given along with the wave characteristics, i.e. different loading cases are described. The extension of the methodology proposed by Wienke and Oumeraci (2005) for the estimation of the impact force has been provided. Next, the improvised methodology has been applied to the measured force response to obtain the impact force. Finally, the results for the different loading cases are discussed in this paper, by comparing with the formulas proposed by Goda et al. (1966) and Wienke and Oumeraci (2005).