www.dergipark.gov.tr
ISSN:2148-3736

El-Cezerî Journal of Science and Engineering
Vol: 10, No: 2, 2023 (253-267)
DOI: 10.31202/ecjse.1202291

ECJSE

Research Paper

Wave Impact Loads on Vertical Circular Cylinder and the Effect of Hydrophobic Surface

Abdallah Mohamed Alwy AL-BEITY[1a], Fatih C. KORKMAZ[1b]*, Bulent GUZEL[2c]

[1]Naval Architecture and Marine Engineering Department, Yildiz Technical University, Istanbul, Turkey
[2]İstanbul Gelişim University, Istanbul, Turkey
*fkorkmaz@yildiz.edu.tr,

Received: 10.11.2022 **Accepted:** 11.05.2023

Abstract: This study presents experimental research on the wave forces affecting cylindrical legs on offshore platforms. The aim was to determine pressure distributions and deformations in the surface properties of altered cylinders by applying a hydrophobic coating. The results show that the hydrophobic coating increases the angle at which water droplets hit the surface, reducing water adhesion. The study used wave loads of 9 cm amplitude and 0.7 Hz frequency, three pressure sensors, and a strain gauge to measure pressure distributions and surface deformations. Findings show that the pressure response for hydrophobic surfaces varied based on the sensor's location, with a decrease in maximum pressure or impact time. Strain measurements for hydrophobic surfaces were 15% higher than for uncoated surfaces due to structural deformation caused by surface property changes. Additionally, hydrophobic cylinders experienced a water rise of at least 1.5 cm compared to uncoated cylinders due to pressure distribution on the hydrophobic surface. The findings suggest that surface modifications, such as hydrophobic coatings, can significantly impact the response of cylindrical structures to wave forces, providing valuable information for offshore platform design and maintenance. Image processing supports this observation, which indicates the variation in the size of the water body to which the surface is exposed.

Keywords: Wave forces, vertical cylinder, hydrophobic surface, structural deformation

1. Introduction

In the world of science and engineering, peculiarly in marine and ocean engineering, waves play a paramount factor in the operation and design of offshore structures. Wave occurrences are generated when water surfaces are disturbed by the wind, as waves travel as swells or ridges. The wind is the prime aspect of the eventual formation of waves in the sea, depending on the sea wave size and the speed of the wind. The friction produced by the blown-up wind towards the sea's water surfaces causes energy transfer from one point to another through the water as a transfer medium. Thus, waves have more force and energy when the wind speed is higher. The molecules of the seawater waves move in an orbital motion in the deep sea, while in shallow water, the movement is linearly toward the shore [1].

The stationary or moving structure is affected by wave impact loads during collisions, which can have a large repercussion on the structure's surface. Wave impact loads always exert enormous forces upon offshore structures, particularly those with cylindrical-shaped legs [2]. Consequently, numerous numerical and experimental studies have been conducted from the past to the present time to understand wave impact loads. Likewise in 1929, Von Karman's study on seaplane landing involved the validation of a cylindrically shaped solid, which was assumed to be a flattened object with a flat-water surface to facilitate the understanding of hydrodynamic forces acting on cylindrical structures [2,3]. This assumption provided a foundation for further research on the topic, enabling a deeper understanding of the hydrodynamic forces that impact cylindrical structures. Wagner (1932)

How to cite this article
Al-Beity A., Korkmaz F. C., Guzel B., "The Effects of Hydrophobic Surface Morphology on Cylindrical Structures under Wave Impact Loads," *El-Cezerî Journal of Science and Engineering*, 2023, 10.(2), 253-267.
ORCID: [a]0000-0003-1858-182X; [b]0000-0001-9250-5265; [c]0000-0001-6915-4209

expanded upon the approach introduced by Von Karman and utilized local jet analysis to address the wedge-entry problem. This method allowed for a more detailed analysis of the hydrodynamic forces impacting cylindrical structures, thus contributing to a deeper understanding of wave impact loads [4].

Over the past and in recent years, investigations of diverse approaches have been carried out through various theories, experiments, and numerical studies that induce impact loads on offshore structures caused by breaking waves. Among these structures, wind turbine offshore structures stand out due to their narrow and long leg members extending from the free surface, with mass concentrated at the pinnacle of the structure [2,5]. Because of the slender and flexible nature of the leg members, these structures are more susceptible to wave and wind loads, which can result in significant structural damage or even collapse. As a result, it is crucial to assess the impact of these forces and design offshore structures to withstand them. To this end, numerous numerical and experimental studies have been conducted to evaluate the effects of wave and wind loads on offshore structures, and various design solutions have been proposed to enhance their resilience[5].

The investigation by Chella et al. [5] into offshore structures, particularly offshore wind turbines, focused on improving the design of the present approach described in their study prior to the one published in 2012. As the occurrence of waves is an area of interest, when traveling from one place to another there is an amount of energy onto these waves that lead to the maximal wave loads on any moving surface or stationary one [6].

Smith et al., in their study, were much more interested in the ability of the body surface structure to endure the maximal wave loads when exposed to them. These impact forces tend to bring about the body structural deformations and eventually collapse, drastically the loss of momentum to the moving structures hence more time for the ship navigation to complete the voyage and ineffective cost since more fuel is used. Most often, they are located in free-flight constructions arranged in a line from lifeboat launching to various digging plans. The impact of fast-moving vessels, such as pontoons and sailboats, as well as fixed structures like offshore rigs, wind turbines, and other similar objects on the surface of waves, cannot be ignored because it reduces structural integrity in one way or another. [2]. Additionally, wave impact stresses that cause wet deck slamming on offshore structures and wave breaking on cylindrical solid structures have significant influences [7]. Von Karman and Wagner's theories were improved to estimate the wave impact loads on the offshore structure under the assumptions of the inviscid flow of fluid, incompressible fluid, and disregarding gravity [2,7].

Other studies, such as Xu et al., investigate the hydrodynamic forces and resilience on net panels under repeatedly extreme wave conditions using model tests in a wave flume. The study found that the net string forces were strongly influenced by wave height, wave period, and net panel orientation, and the net string forces were dependent on the steadiness and Keulegan-Carpenter number (KC) of the net strings as was in the material of the net. A mathematical model was developed using a dimensional analysis approach and validated by comparing the predicted forces with the experimental data. The study provides valuable insights into the behavior of net panels in extreme waves and could have practical applications for designing and operating offshore structures [8]. It is vital to understand that the hydrodynamic loads can be adequate to affect the response of structures over the threshold limit, which is known as the hydro-elastic effect [9]. It eventually occurs with wind turbine foundations as well as other high coastal/marine structures, which is a fairly typical occurrence in maritime and coastal engineering. For instance, [10] discovered that even gently sloping waves can cause wind turbine foundations in shallow seas to vibrate significantly and eventually may cause deformations.

Liu et al. performed numerical simulations to investigate the wave impact on a fixed jacket platform. They used the smooth particle hydrodynamics method to simulate the wave-structure interaction. The results showed that the wave impact caused stresses and significant structural deformations on the platform [11]. Shi et al. conducted an experimental study to investigate the hydrodynamic performance of a heaving buoy assembled on a net cage platform. They measured the platform's motions under various wave conditions and analysed the dynamic responses of the structure. The results showed that the movement of the entire system was affected by the hydrodynamic forces [12]. Huang et al. computational fluid dynamics (CFD) study that aimed to investigate the hydrodynamic performance of a semi-submersible structure, the Wind turbine platform, under different wave conditions. They studied the motions and strains of the platform under various wave conditions and analysed the system's dynamic responses. The results showed that as the wave height and period rose, so did the platform's motions and strains [13].

In another investigation, Chen et al. assessed the impact of a porous wall on wave impacts on a vertical wall. They discovered that the deployment of this wall lowered the wave impact load and energy dissipation on the wall. The wall significantly reduced turbulence intensity and altered the flow pattern, indicating that such a design can help minimize wave impacts on coastal structures [14]. Also, another study by Korkmaz et al. examined the impact of curtain-type barriers versus no barriers on the sloshing loads in a tank. The curtains can significantly modify the movement of fluid mass and reduce wave impact loads on tank side walls. The findings imply that these improvements in structural surfaces can be advantageous for enhancing navigational safety and mitigating structural damage to tanks [15].

Furthermore, the usage of innovative materials in offshore constructions has been investigated as a technique for lowering wave impact loads. For example, Saadatmanesh et al. describe a study using Fiber Reinforced Polymer (FRP) composites to strengthen concrete beams under impact loading conditions. Although their research does not directly address the usage of FRP composites in offshore structures, it provides an understanding of their exceptional strength and stiffness, which are crucial factors in their potential to minimize wave impact forces on offshore structures. Their study shows that using FRP composites can significantly increase the load-carrying capacity and ductility of the concrete beams under impact-loading conditions. The results also demonstrate the importance of considering the behavior of FRP composites under impact-loading conditions when designing and constructing structures susceptible to wave impacts, such as offshore structures [16]. The study of ÇeltinKarakaya and Ekşi suggests that the design and material of the core in structures can substantially affect their deformation behavior under loading. The structured surface may exhibit strong solid surface characteristics simply by changing the shape and materials used. This discovery implies that altering the structure surface and shape of offshore structures can also lessen wave impact loads and enhance their general performance[17]. In another study by EyüpYeter and Doğru proposes a significant decrease in wave impact loads on structure surfaces by utilizing creative solutions, such as composite materials with excellent impact resistance. By understanding the mechanical behaviors of these materials under impact loads, cost-efficient alternatives can be designed and implemented for safer offshore operations[18].

Wave impact loads supply a substantial problem to offshore structures because they can cause structural damage, lower performance, and environmental issues. The works covered in this paper illustrate several ways to minimize wave impact loads, such as altering the surface characteristics of offshore structures, employing innovative materials, and enhancing the design and shape of offshore structures. These methods can mitigate the effect of wave stresses on offshore constructions, resulting in higher safety, lower maintenance costs, and better environmental protection.

The relationship between wave impact loads acting on maritime constructions and solid surface features is well-recognized. Although hydrophobic material has the potential to enhance the elastic-plastic properties of solid surfaces, previous studies have not been successful. Hydrophobic material increases the contact angle between water and a solid surface, thereby making it more likely for the hydrophobic surface to exhibit elasticity characteristics when interacting with water compared to hydrophilic surfaces. The main objective of this work is to comprehend how modifying the surface properties of offshore structures can reduce the effect of the occurrence of the impact of wave loads on them. The paper provides a clear understanding and demonstrates how wave impact loads on cylinders respond differently when one of the cylinder models is coated with a hydrophobic material to alter its surface properties.

1.1. Hydrophobicity Effect

A water droplet produces a spherical pellet shape when deposited on a hydrophobic surface, such as a lotus leaf, attributable to the surface's non-polarity and reluctance to dissolve with water. This phenomenon is known as the "lotus effect," it was initially discussed in 1997 by Barthlott and Neinhuis [19]. The lotus effect is caused by the surface's hierarchical micro and nanostructure, which forces water droplets to minimize interaction with the surface thus forming a spherical morphology. Hydrophobic surfaces have low surface energy and are often employed in self-cleaning and anti-fouling applications because they resist water and keep pollutants from adhering to the surface [20]**.** In the event of wave impact, the surface's wetting characteristics of hydrophobic materials affect how water interacts with the structure under impact loads [21]. The hydrophobic materials tend to repel water, so water droplets rest on top of air bubbles instead of touching the surface, which means the contact area is small, reducing friction and allowing the droplets to glide easier when there is a minimal contact area. Hydrophobic materials use surface irregularities to contain air at the bottom of the droplet, which, when combined with the structure's surface, creates contact angles greater than 90° as seen in Figure 1(a).

Therefore, the less surface area a water droplet has in contact with solid objects, the more freedom it has to glide. Due to the water droplet lying on top of the airspace on top of the structure's surface, waves traveling toward the solid surface will produce contact angles greater than 90°. The result of slippage caused by the greater contact angle minimizes the drag coefficient in the turbulent and laminar flow due to the hydrophobic effects. Hence the droplet will be free to move without encountering drag resistance [22]. These types of formations are said to be hydrophobic as can be seen in Figure 1(a).

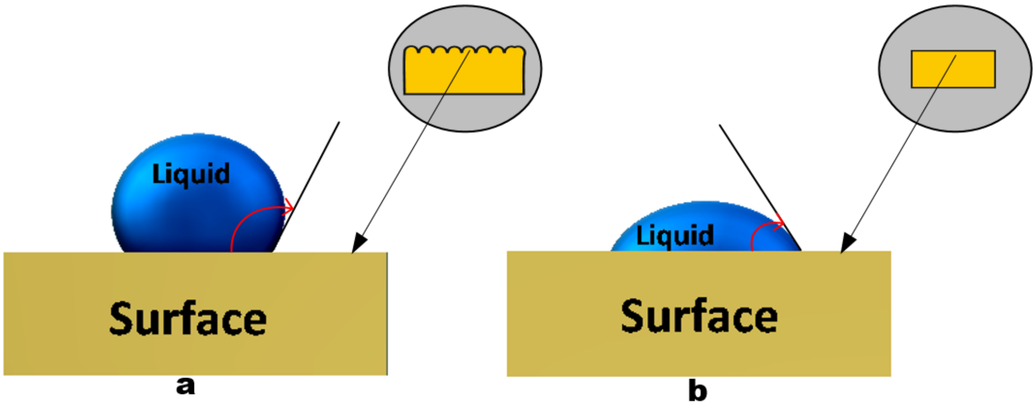

Figure 1. Schematic Diagram for Surfaces under water drops (a)Hydrophobic Effect, and (b) Hydrophilic.

Hydrophilic surfaces, on the other hand, such as glass or metals, have a high surface energy and interact aggressively with polar water molecules. When a water droplet is deposited on a hydrophilic surface, the surface tension of the water and the attraction interactions between the water molecules and the surface cause it to spread out and soak the surface [23]. Hydrophilic refers to a surface that causes water droplets to have a flat base and a sizable contact area. Also, hydrophilic surfaces have a high affinity for water, creating a flat base and a larger contact area, which prevents the formation of gas bubbles at the bottom of the water droplet, resulting in friction between the droplet and the surface. Since gas bubbles are unstrapped on the bottom of the water droplet, hydrophobic materials do not allow fluid to pass through the surface, thus preventing friction between the water droplet and the [24]**.** This phenomenon is illustrated in Figure 1(b). Hydrophilic surfaces are important in many applications, including wetting and adhesion, catalysis, and biomedical devices [25].

1.2. Mathematical Formulation

In comparison to the wave duration with significant amplification, the impact on the structure occurs over an abbreviated time. The structure and wave impact point are indicated by the darkened region in Figure 2. The maximum value is for plunging waves, that are determined experimentally to have a curling ratio of 0.5, whereby H_b represents wave height, η_b is surface elevation, R is the cylinder's radius, C is wave celerity approaching the cylinder, and $\boldsymbol{\lambda}$ is a curling factor that relies on the form of waves [23,24]. SWL means Still Water Level.

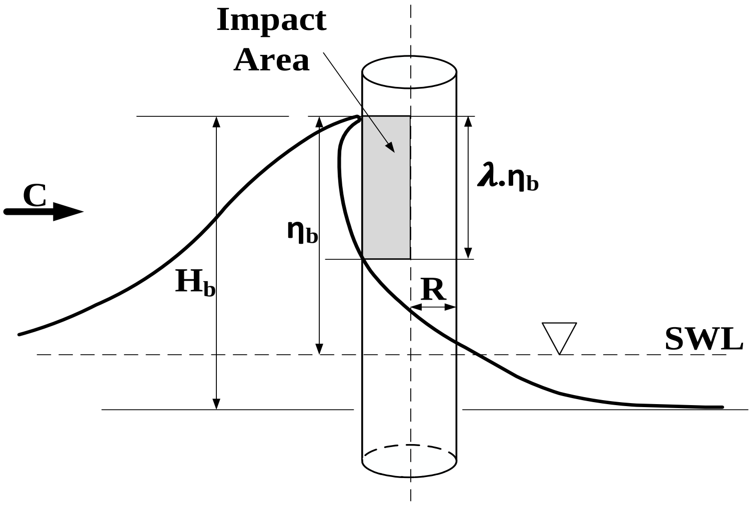

Figure 2. Definition Sketch [28]**.**

These forces are the result of the front wave's severe interactions with the structure. At first, the line force is greatest when time, t, equals 0 [28].The following equation yields the line force.

$$f = 2 \cdot \pi \cdot \rho \cdot R \cdot C^2 \tag{1}$$

Throughout wave impacts, the time limit of the impact is an important consideration because the structure is subjected to a strikingly large compressive force magnitude in an instant. The following equation provides the impact's period.

$$T = \frac{13}{32} \cdot \frac{R}{C} \tag{2}$$

Based on the surface features of a similar structure, the impact focuses at one location before dispersing over the surface. The normal impact force F is described in equation 3 as follows for more components [23,25].

$$F = \lambda \cdot \eta_b \cdot \rho \cdot R \cdot C^2 \cdot \left(2 \cdot \pi - 2 \cdot \sqrt{\frac{C}{R} \cdot t} \cdot Ar\tanh \sqrt{1 - \frac{1}{4} \cdot \frac{C}{R} \cdot t}\right) \tag{3}$$

$$for \quad 0 \le t \le \frac{1}{8} \cdot \frac{R}{C}$$

2. Experimental Setup

In the Laboratory of Hydraulics and Coastal Engineering of the Civil Engineering Department at Yildiz Technical University, the tests were conducted in the wave flume. In Figure 3., the experiment's setup is depicted. The flume has dimensions of 20 m in length by 1 m in breadth and 1 m shallow. An irregular/regular wavemaker with a range of frequency values and amplitudes was connected to the end of the canal, and the HR Wave Dataset program was used to collect and analyze the data. Using the wavemaker shown in Figure. 3, random and sinusoidal waves were produced.

Figure 3. Photographs of experimental setup.

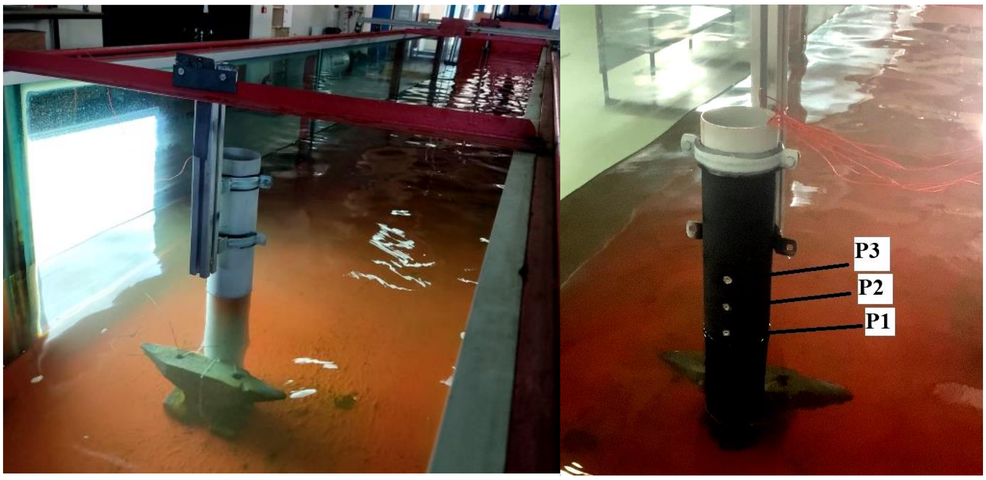

Figure 4. A view of cylinder model and other equipment.

2.1. Materials and Cylinder Models

A LED light was used to illuminate the striking region, and the level of water in the canal was set at 0.5 m to pinpoint the increase in wave amplitude from the designated amplitude and frequency. The cylinder is placed 10 meters from the wavemaker in the center of the flume.

An aluminium clamp was used to attach the cylinder to the flume's rail shown in Figure 4 at its top. The experiment aimed to investigate the motion of cylindrical solid objects floating in offshore settings by simulating them in a small-scale wave flume. The study showed that a mass moored with tension leg mooring wires maintains its motion during a wave period unless there is a change [29]. To prevent any movements and instabilities of the structure that could coincide with the collected readings and avoid maximum loads, a hefty 20 kg iron was employed to hold the cylinder at the bottom, ensuring wave dynamics were not affected.

In order to study the impact of surface characteristics on wave stresses, two cylinders were chosen to compare the effects of hydrophobic and hydrophilic materials on their surfaces. The study focused on cylindrical structures as they are the most commonly used offshore structures. The cylinders were subjected to a wave with an amplitude of 9 cm and a frequency of 0.7 Hz. The malleable Polyvinyl Chloride (uPVC) cylinders were given a smooth texture by painting them with acrylic paint. In addition, one of the cylinders was sprayed with hydrophobic coating manufactured by WetProof Inc. Although the coating caused an increase in surface contact angle, there were no notable changes in the geometry or mass of the cylinder surfaces. The same procedure was applied to the study by [30] in investigating the water entry of bodies with constant deadrise angles under hydrophobic effects. Their findings suggest that hydrophobic coatings can significantly reduce the drag coefficient of objects under wave impact, leading to increased slippage and reduced resistance without changing the body mass of the geometry. These results support the notion that hydrophobic coatings can improve the performance of structures in the water, as seen in the case of the hydrophobic-coated cylinder in our experiment [30]**.**

Table 1. The details of each cylinder.

Cylinder Designs	Hydrophobic Coated	Uncoated (Hydrophilic)
Materials	Hydrophobic	Polyvinyl chloride pipe (uPVC)
Diameter	11 cm	11 cm

We divided the study into two sections and took pressure measurements on three points on the cylinder surface where wave loads conflicted in the first section. In the second section, we used strain gauges to measure the surface elasticity of the structure during wave impact.

We used a wavemaker to generate waves with varying frequencies and amplitudes, and we selected a wave amplitude of 9 cm and a frequency of 0.7 Hz for our study. We conducted experiments on cylindrical structures with hydrophilic and hydrophobic surfaces. We installed pressure sensors and a strain gauge on the cylinders to measure the impact of the waves.

For the pressure measurement, we installed three SHLLJ PCM300D pressure sensors on the wave-facing end of the cylinder surface at 5 cm intervals. The first sensor, P1, was placed 2 cm above the water surface in the center of the cylinder surface. P2 was placed 5 cm above P1 at a height of 7 cm, and P3 was placed at 12 cm above the water surface. These sensors have a maximum load of 0.4 bar, a response time of 20 s (50 kHz), a diaphragm radius of 1.75 mm, and a sensor accuracy of 0.5%. For strain measurement, we installed a Tokyo Sokki Kenkyujo Co. Ltd.-produced Type WFLA-6-11-3L strain sensor on the inside of the cylinder surfaces, close to the water surface. We exposed the cylindrical structures to waves with a 9 cm amplitude and 0.7 Hz frequency and collected sensor data for signal analysis. We also obtained videos of the experiments for further processing. We analyzed fluctuations in pressure measurements whenever the surface properties of the cylinders changed. The strain gauge measured the cylinders' deformability and calculated their maximum elastic properties and the mechanical stimulation caused by wave impact loads. We analyzed the impact of wave stresses based on the positioning of each pressure sensor close to the water surface and the cylinders' distortion due to these wave loads. Our analysis allowed us to examine the surface properties of the cylindrical structures.

Examining the results obtained from the hydrophilic cylinder in Figure 5, it is apparent that each sensor has three peaks that are close to each other and have negligible differences in pressure. Furthermore, the P1 peaks had the highest-pressure values, P2 had intermediate values, and P3 had the lowest pressure. These observations validate the certainty of the experiment since the results are consistent and reproducible.

Nevertheless, it is crucial to acknowledge potential sources of uncertainty that could impact the experiment's outcome. Firstly, the measurement uncertainty of the pressure sensors could have affected the overall results and introduced unreliabilities. Secondly, inaccurate positioning of the pressure sensors could have also resulted in faulty readings and introduced unreliabilities.

Furthermore, environmental conditions such as wave height, frequency, and direction may change during the experiment, resulting in unpredictability in the results. The experiments should be carried out under controlled environmental circumstances to reduce this source of uncertainty.

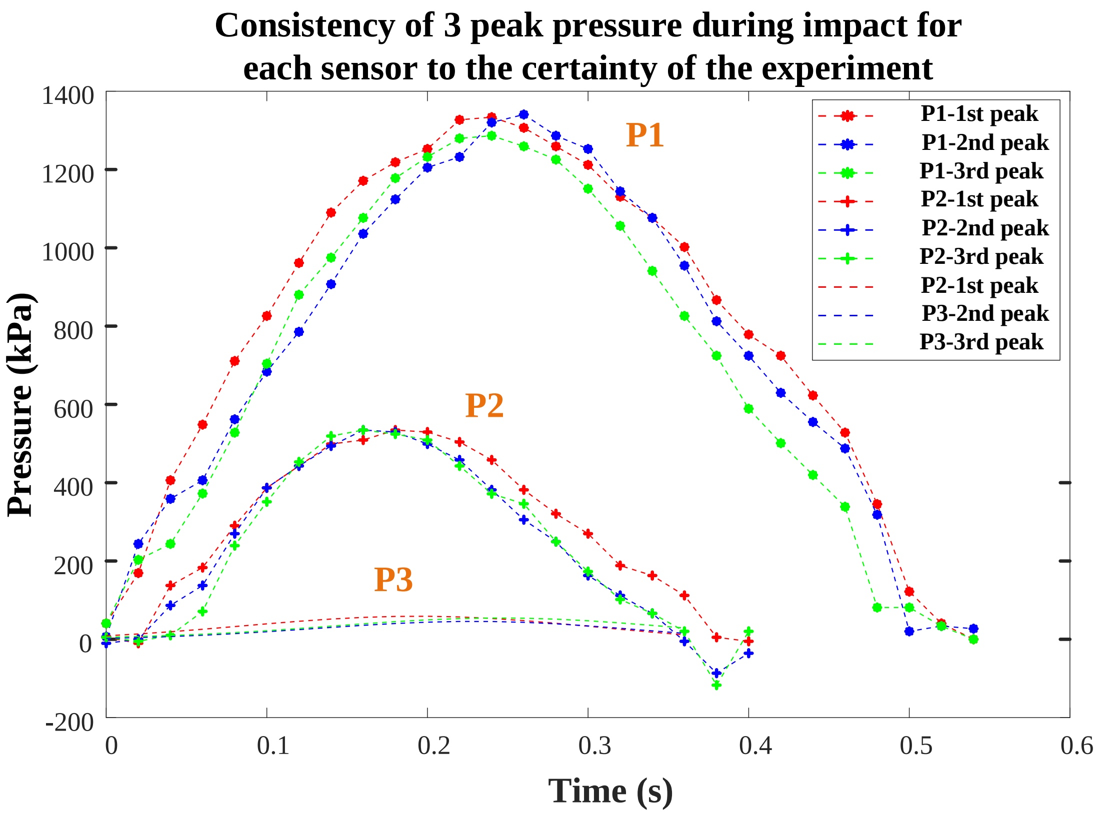

Figure 5. Uncertainty analysis of the experiment with pressure sensors.

3. Results and Discussion

In the phenomenon of the wave loads impacting the offshore structure usually, a few scenarios may occur accordingly such as vibration, failure of the structure member, noise to the sea environment, and immediate loss of momentum to the moving structures. The abovementioned outcomes can have substantial economic and environmental repercussions, emphasizing the significance of adequate maintenance and management techniques for marine infrastructure. As a result, developing innovative and sustainable solutions to these difficulties and ensuring the safe and effective operation of maritime infrastructure is critical. The study investigated the impact of waves on offshore structures, using an experiment conducted at a wave height of 9 cm and a frequency of 0.7 Hz. Data were collected using pressure sensors and strain gauges. Local pressure measurements were taken at three specific locations above sea level (SWL), while global surface measurements were used to compare the elasticity of the cylinder's surfaces. The study aimed to understand how waves affect offshore structures and their surfaces, which can help to design safer and more durable offshore structures.

3.1. Local Pressure Points and Amplitude Increment

The three sensors placed on the surfaces of the cylinders recorded pressure peaks and water surface elevation during impact time. The videos recorded were processed to show that the amplitude rise was higher in the case of hydrophobic surfaces than in the case of hydrophilic surfaces.

Figure 6 presents the processed images from the videos for both cases of cylinders with different time steps of five snapshots labeled as (a_1-a_5) and (b_1-b_5), respectively. The figure shows the impact time for each image and the water surface elevation during wave impact on the cylinders. The water surface elevation (amplitude rise) is higher in the case of hydrophobic surfaces than in the case of hydrophilic surfaces. Thus, the water pressure distribution is higher in the hydrophobic cylinder.

During the impact of the uncoated cylinder in a time step of 1.58 s, the rise of the wave amplitude increased along the surface to a higher elevation by 6.25 cm, as shown in Figure 6(a_1). In contrast, the amplitude rise along the surface of the hydrophobic surface increased to a higher elevation of 9.4 cm at the impact peak time of 1.65 s, as shown in Figure 6(b_1). The pressure distribution seems to differ between the two cases where the hydrophobic coated surface tends to have more climb up.

Figure 6(a_2) shows the impact at the time step of 1.717 s with just a 7.9 cm wave amplitude rise in elevation along the cylinder's surface. In contrast, for the hydrophobic case in part (b_2), the amplitude increment was more by 11.5 cm at the time of 1.65 s. The rise of the amplitudes for both uncoated and coated cases concerning their time step during the impact is 6.24 cm at 1.892 s and 10.4 cm at 1.828 s, respectively, as shown in Figure 6(a_3) and (b_3).

At the noted time of a peak impact of 1.999 s, the amplitude rise toward the surface elevation increased by 10.2 cm for the hydrophobic surface, as shown in Figure 6(b_4), whereas for the uncoated surface, the impact occurred at the time step of 2.064 s with an increased height of 8 cm, as shown in Figure 6(a_4). In Figure 6(a_5) and (b_5), the increase in wave amplitude height was 8 cm during the peak impact time of 2.233 s and 13 cm during the peak impact time of 2.168 s.

For the hydrophobic coated surfaces cylinder, the wave amplitude rise toward the surface elevation of the cylinder is higher than that of the hydrophilic surfaces. Hence, these two cases exhibit differences in their surface characteristics, therefore, behave differently during wave impacts, with the pressure distribution along the surface of the cylinders being influenced by their respective properties. he three installed pressure sensors measured the focal points, and the pressure distribution was present along the surfaces. Hence, the maxima impact cannot be on a single locality but instead distributed along the surface. This effect is seen more in the hydrophobic coated cylinder than the uncoated cylinder because of its remarkable repellent surface characteristics. The hydrophobic coating caused water to rise of at least 1.5 cm compared to the hydrophilic cylinder, thus, decreased the impact force by dispersing pressure across the surface.

The two different surfaces of the cylinders were investigated individually for their reactions when exposed to wave impact forces. Since P1 was the nearest to the free surface at 2 cm above water level, it was anticipated to have a higher pressure than other sensors.

As the pressure distribution along the surface is not much for the hydrophilic surfaces, air gaps on the hydrophobic surfaces are fully covered with water, and no space for air to be trapped underwater drops. Hence, the low pressure for the hydrophobic case will not have a variation of pressure and pressure impact dynamics[31]. The jet flow produced during collision has a considerable magnitude and increases even more when hydrophobic coating are present on the surface [32] [22]. In addition to reducing impact force on the structures, hydrophobicity causes immediate jet flow separation, which reduces any subsequently applied forces resulting from the interaction of split jet flows. Hence water climbing toward surface elevation will be higher than in the hydrophilic case [24].

In the study, the height of water elevation or the amplitude of the water wave during the impact is related to the pressure distribution on the cylinder surface. When a water wave impacts a solid surface,

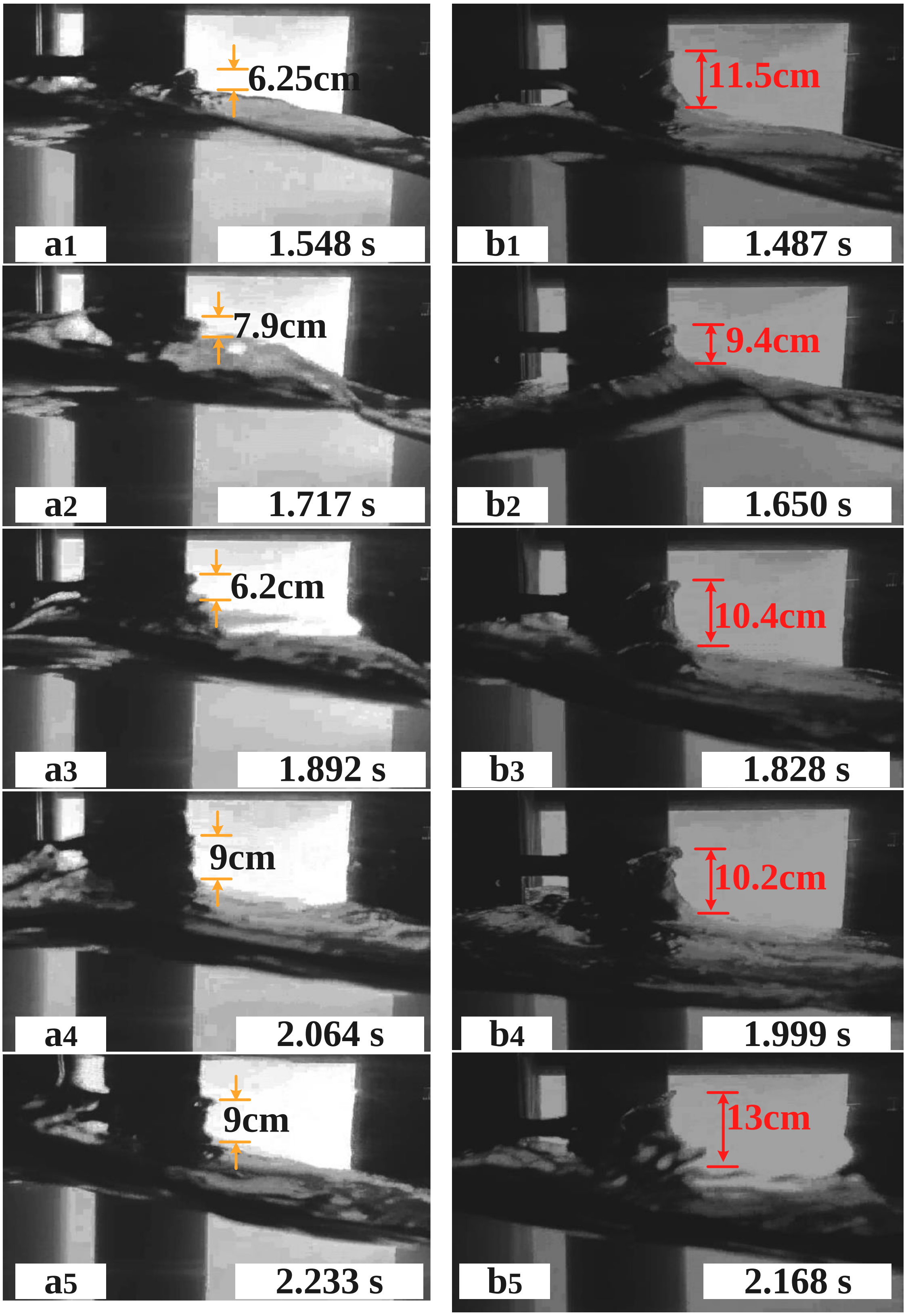

Figure 6. Snapshots of the water surface elevation profiles at different time steps for both cases uncoated cylinder and hydrophobic coated cylinder labelled as (a_1-a_5) and (b_1-b_5), respectively for the wave profile of 9cm Amplitude and Frequency of 0.7Hz.

it generates pressure distribution that varies along the surface, and the magnitude of pressure depends on the height of the water wave.

In the study, pressure sensors were used and placed on the cylinder surface to measure the local pressure distribution during the impact. We also recorded videos of the wave impacts to visually analyze the behavior of the water wave and its interaction with the cylinder surface.

Based on the results, the observation was that the water elevation or amplitude of the water wave was higher for the hydrophobic coated cylinder compared to the uncoated cylinder. It indicates that the pressure distribution was also higher for the hydrophobic coated cylinder. We attributed this to the hydrophobic nature of the surface, which repels water and reduces the impact force on the cylinder. This results in less jet flow separation and, hence more water climbing toward the surface elevation, resulting in higher water elevation and pressure distribution.

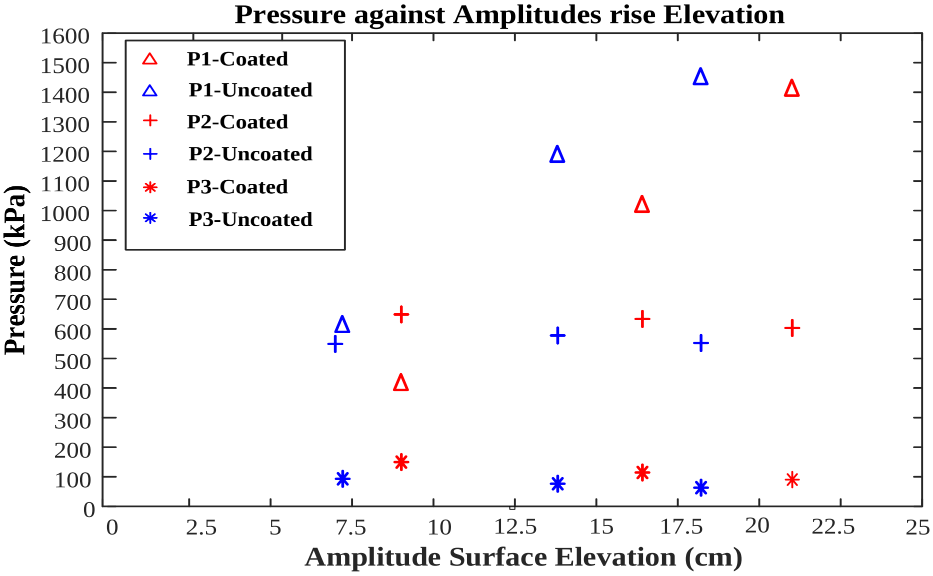

Figure 7. Wave Profile of 18cm Wave height and O.7Hz Frequency, The Impacting Pressure for both cases on all sensor's region against Surface Elevation.

Figure 7, the behavior of the two cylinders under wave pressures at different wave amplitude rises on their surfaces. The graph also illustrates the impact on both cylinders at the positions of all three sensors. As seen in Figure 7, the time taken for the collision on each cylinder differs due to their surface characteristics. The pressure impact on the cylinder is proportional to the cylinder's surface elevation in both cases, at P1. However, the uncoated surface cylinders had more pressure than the latter case at the P1 impacting area since sensor P1 is closer to the water surface by 2cm above the water surface.

The hydrophilic surface properties are considered to be smooth and tend to experience higher pressure than hydrophobic surfaces, as discussed by Güzel and Korkmaz in their study [33]**.** The study indicated that the maximum impact loads on the cylinders had pressure impact dynamics due to air entrapment on the surface. At P1, there will be no space for air entrapment for the hydrophobic cylinder, as water drops will take over the roughness of the surface instead of resting above the confined air. The absence of air dynamics in the impact region will result in neither pressure impact dynamics nor pressure variability in the hydrophobic cylinder [31] The area with the most impact pressure is dominated by more pressure due to the entrapped air [34]. Therefore, the hydrophilic surface will bear more pressure impact at a lower surface elevation than the hydrophobic surface for the first sensor.

The anticipated outcome to show pressure impacts on the hydrophobic cylinder is higher than that of the hydrophilic surface at P2. This phenomenon occurs because the availability of air around P2 is higher, as P2 is located 7cm above the Still Water Level (SWL). Thus, the residence of air bubbles on the surface of the hydrophobic cylinder will lead to water drops lying on top of the air on the grooved surface. As a result, more water will climb up the surface elevation in the case of a hydrophobic surface. The water rise is caused by the water drops when water creates a 90° contact angle on the surface, and the same water drops lie on top of the trapped air when the wave hits the surface. Hence, water drops cannot contact the cylinder's indented surface due to the trapped air under it [24]**.** Thus, in Figure 7, higher pressure is noted in the hydrophobic case because water drops never hit the indented surface but rather lay on top of the air where water rises toward the surface elevation. Hence, pressure distribution along the surface was present due to the air dynamic for the hydrophobic case, unlike in the hydrophilic case, where more stresses from the impact will concentrate more on the impact region. The pressure at P2 reduces as the amplitude surface elevation of the cylinder increases for both cases since the impact was happening farther away from the point of location toward the upper elevation, even though for the hydrophobic case pressure is still higher.

In Figure 7, the graph shows that pressure tends to decrease as the amplitude surface elevation increases in both cases for sensor P3. The expected result of the Hydrophobic cylinder having more pressure than the hydrophilic cylinder is shown in Figure 7 and was obtained during the experiment at the third sensor P3. The higher pressure in the case of the coated cylinder is due to the enormous amount of air on the grooved surface of the coated cylinder. Hence, the water drop can lay perpendicular to the surface, allowing air entrapment. Air entrapment means the pressure distribution along the surface toward the surface elevation will be high. Unlike the uncoated cylinder, no pressure distribution occurs since the air dynamic, in this case, is non-existent, and thus, no water climbs toward the surface elevation. At P3, the sensor is 12cm above SWL, and the results showed more pressure for the Hydrophobic surface because of its unique property of repelling water.

3.2. Global Surface Measurements

Another measurement taken during the experiment involved a strain test on the surface of the cylinders, not just three pressure measurement points. This test measured the elasticity between the two cylinders by examining how the cylinder surface deformed under the acting forces. The strain sensor placed on the cylinder's forefront near Still Water Level (SWL) above the free surface measured strain. Figure 8 displays the strain data of the two cylinders under wave impact loads.

Of the two cylinders, the one coated with hydrophobic material exhibited higher strain values compared to the uncoated hydrophilic cylinder. The graph shows five peak impacts in one second for each cylinder. Each wave impact on the cylinders of each cylinder is deformed distinctively in three peaks with assorted sizes in magnitude for the peak of the two cylinders. The hydrophobic coated cylinder deformed more compared to the uncoated cylinder.

In the figure, the hydrophobic coated cylinder returns temporarily to zero position, contrasting with the hydrophilic cylinder due to the formation of two additional higher peaks compared to the latter case. This indicates that the coated cylinder has more deformability during the crash. Since the time for the uncoated cylinder to reach its original position at zero is higher than the coated cylinder, the surface elasticity may fail. Hence, permanent deformation may occur for the uncoated cylinder.

It is observed in the figure that the hydrophobic coated cylinder's deformability is much higher than in the hydrophilic case. Specifically, the hydrophobic coated cylinder exhibited 15% higher strain values than the hydrophilic cylinder. This indicates that the hydrophobic coating enhances the cylinder's ability to deform under impact loads, which can be attributed to the coating's ability to trap more air on the surface, resulting in increased surface elasticity. This increased deformability can have both positive and negative implications in real-world scenarios. On one hand, it may help absorb impact forces and reduce damage to the cylinder. On the other hand, it may increase the risk of permanent deformation or failure under severe impact loads. Further studies are needed to evaluate the trade-offs of using hydrophobic coatings in practical applications.

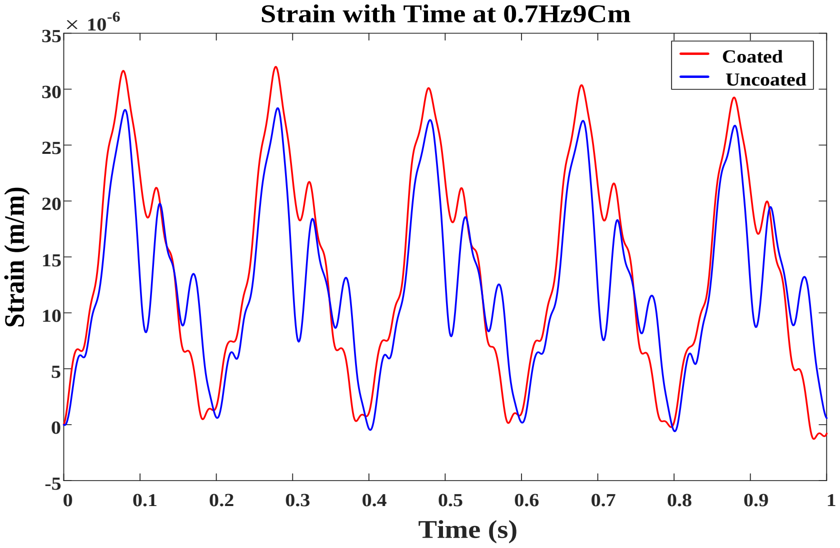

Figure 8. Comparison of structural deformation between hydrophobic uncoated cylinder.

4. Conclusions

The study demonstrates that modifying the surface properties of offshore structures using hydrophobic material can reduce the impact of wave loads on them. Wave impact loads can cause damage, lower performance, and environmental issues on offshore structures. Hydrophobic coatings can increase the elasticity of solid surfaces, decreasing wave impact loads on offshore structures. The hydrophobic coating reduced the impact force by dispersing pressure across the surface and produced a better outcome by keeping the water off the surface and spreading the pressure evenly. The hydrophobic coating caused a water rise of at least 1.5 cm compared to the hydrophilic cylinder, thus, decreasing the impact force by dispersing pressure across the surface. The strain measurements showed that the hydrophobic coating led to higher strain readings, and the elastic modulus of the uncoated cylinder was more susceptible to failure. Hydrophobic coating has higher strain values by approximately 15% compared to the uncoated cylinder. The hydrophobic coating allowed for greater flexibility and strain recovery, making it more resilient to wave impacts. The hydrophobic coating enhances the cylinder's ability to deform under impact loads, which is attributable to the coating's ability to trap more air on the surface, resulting in increased surface elasticity. Hydrophobic coatings can reduce the influence of wave stresses, resulting in higher safety, lower maintenance costs, and better environmental protection of offshore constructions. We recommended conducting further tests at higher elevations to verify the findings near the Still Water Level. Further studies are needed to evaluate the reciprocations of using hydrophobic coatings in practical applications. It is essential to consider sources of uncertainty such as measurement uncertainty, sensor positioning, and variability in environmental conditions during the experiment. Thoughts, projections or ideas of the authors about cost and feasibility of hydrophobic coating may be inserted here.

Authors' Contributions

AA, FCK and BG. The authors conducted experiments, analysis studies and writing of the article. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

References

[1]. Y. Goda, “Random Seas and Design of Maritime Structures,” *World Scientific*, vol. 33, 2010.

[2]. N. J. Smith, P. K. Stansby, and J. R. Wright, “The Slam Force on a Flat Plate in Free Flight due to Impact on a Wave Crest,” *Journal of Fluids Structures*, vol. 12, no. 2, pp. 183-196, Feb. 1998, doi: 10.1006/jfls.1997.0132.

[3]. V. Karman, “The impact on seaplane floats during landing,” *NACA Technical Note NACA TN321*, 1929.

[4]. H. Wagner, “Uber stoss und Gleitvorgänge an der Oberfläche von Flüssigkeiten,” *Zeitschrift fur Angewandte Mathematik und Mechanik*, vol. 12, pp. 193-215, 1932.

[5]. M. A. Chella, A. Tørum, and D. Myrhaug, “An overview of wave impact forces on offshore wind turbine substructures,” *Energy Procedia*, vol. 20, pp. 217-226, 2012, doi: 10.1016/j.egypro.2012.03.022.

[6]. M. H. Nokob, “The Energy Capture Analysis of A Cylinderical Wave Energy Converter,” vol. PhD, 2011.

[7]. S. E. Hirdaris et al., “Loads for use in the design of ships and offshore structures,” *Ocean Engineering*, vol. 78, pp. 131-174, Mar. 2014, doi: 10.1016/j.oceaneng.2013.09.012.

[8]. T. J. Xu, G. H. Dong, M. F. Tang, J. Liu, and W. J. Guo, “Experimental analysis of hydrodynamic forces on net panel in extreme waves,” *Applied Ocean Research*, vol. 107, pp. 102495, 2021, doi: 10.1016/j.apor.2020.102495.

[9]. C. Lugni, A. Bardazzi, O. M. Faltinsen, and G. Graziani, “Hydroelastic slamming response in the evolution of a flip-through event during shallow-liquid sloshing,” *Physics Fluids*, vol. 26, no. 3, pp. 032108, 2014, doi: 10.1063/1.4868878.

[10]. E. J. de Ridder, P. Aalberts, J. van den Berg, B. Buchner, and J. Peeringa, “The Dynamic Response of an Offshore Wind Turbine With Realistic Flexibility to Breaking Wave Impact,” *Ocean Space Utilization; Ocean Renewable Energy*, vol. 5, pp. 543-552, 2011, doi: 10.1115/OMAE2011-49563.

[11]. H. Liu, C. Zhao, Z. Jiang, H. Su, and X. Qu, “Numerical investigation of wave run-up and impact forces on large offshore jacket platforms,” *Ocean Engineering*, vol. 266, no. P1, pp. 112539, 2022, doi: 10.1016/j.oceaneng.2022.112539.

[12]. H. Shi, X. Dong, L. Feng, and Z. Han, “Experimental Study on the Hydrodynamic Performance of a Heaving Buoy Assembled on a Net Cage Platform,” *Journal of Ocean University of China*, vol. 18, no. 5, pp. 1031-1040, 2019, doi: 10.1007/s11802-019-4028-x.

[13]. Y. Huang, Y. Zhuang, and D. Wan, “Hydrodynamic Study and Performance Analysis of the OC4-DeepCWind Platform by CFD Method,” *International Journal of Computational Methods*, vol. 18, no. 4, 2021, doi: 10.1142/S0219876220500206.

[14]. Y. H. Chen, T. Chu, and K. H. Wang, “Analytical and Experimental Investigation of Waves Propagating through Thin, Porous Walls for Coastal Protection Applications,” *J. Coast. Res.*, vol. 35, no. 6, pp. 1294-1306, 2019.

[15]. F. C. Korkmaz, K. Yigit, and B. Güzel, “Perde Tipi Engellerin Çalkantı Yüklerini Azaltma Etkileri Üzerine Deneysel Bir Çalışma,” *El-Cezeri Fen ve Mühendislik Dergisi*, vol. 8, no. 3, pp. 1149-1157, 2021, doi: 10.31202/ecjse.899736.

[16]. T. Tang and H. Saadatmanesh, “Analytical and experimental studies of fiber-reinforced polymer-strengthened concrete beams under impact loading,” *ACI Struct. J.*, vol. 102, no. 1, pp. 139-149, 2005, doi: 10.14359/13539.

[17]. S. ÇetinKarakaya, “Oluklu Çekirdekli Sandviç Panellerin Deformasyon Davranışı Üzerine Simulasyon Çalışması,” *El-Cezeri Fen ve Mühendislik Dergisi*, vol. 9, no. 2, pp. 843-852, 2022.

[18]. M. H. EyüpYeter, "Karbon/Epoksi ve Cam/Epoksi Kompozitlerin Düşen Ağırlık Darbe Testi Altındaki Davranışlarının Simule Edilmesi," *El-Cezeri Fen ve Mühendislik Dergi*si, vol. 7, no. 2, pp. 895-905, 2020.

[19]. W. Barthlott and C. Neinhuis, "Purity of the sacred lotus, or escape from contamination in biological surfaces," *Planta*, vol. 202, no. 1, pp. 1-8, 1997, doi: 10.1007/s004250050096.

[20]. D. Ebert and B. Bhushan, "Durable Lotus-effect surfaces with hierarchical structure using micro- and nanosized hydrophobic silica particles," *J. Colloid Interface Sci.*, vol. 368, no. 1, pp. 584-591, 2012, doi: 10.1016/j.jcis.2011.09.049.

[21]. R. J. Daniello, N. E. Waterhouse, and J. P. Rothstein, "Drag reduction in turbulent flows over superhydrophobic surfaces," *Phys. Fluids*, vol. 21, no. 8, pp. 085103, 2009, doi: 10.1063/1.3207885.

[22]. B. Guzel and F. C. Korkmaz, "Experimental investigation of water entry impact on hydrophobic surfaces," *Proceeding International Conference of Offshore Mechanical and Arct Engineering - OMAE*, vol. 7, pp. 2022, 2015, doi: 10.1115/OMAE201541729.

[23]. J. Brier and lia dwi jayanti, "Hydrophilic and Superhydrophilic Surfaces and Materials," vol. 21, no. 1, pp. 1-9, 2020, [Online]. Available: http://journal.um-surabaya.ac.id/index.php/JKM/article/view/2203.

[24]. F. C. Korkmaz and B. Güzel, "Water entry of cylinders and spheres under hydrophobic effects; Case for advancing deadrise angles," *Ocean Engineering*, vol. 129, pp. 240-252, 2017, doi: 10.1016/j.oceaneng.2016.11.021.

[25]. G. A. Somorjai, "Surface reconstruction and catalysis," *Annu. Rev. Phys. Chem.*, vol. 45, no. 1, pp. 721-751, 1994, doi: 10.1146/annurev.pc.45.100194.003445.

[26]. J. Wienke, U. Sparboom, and H. Oumeraci, "Breaking wave impact on a slender cylinder," *Coast. Eng. 2000 - Proc. 27th International Conference of Coastal Engineering ICCE 2000*, vol. 276, pp. 1787-1798, 2000, doi: 10.1061/40549(276)139.

[27]. J. Wienke, U. W. E. Sparboom, and H. Oumeraci, "Theoretical Formulae for Wave Slamming Loads on Slender Circular Cylinders and Application for Support Structures of Wind Turbine," Coast. Eng. 2004 - Proc. 29th International Conference of Coastal Engineering ICCE 2004, no. 1, pp. 1-10, 2004, [Online]. Available: https://doi.org/10.1142/9789812701916_0324.

[28]. J. Wienke and H. Oumeraci, "Breaking wave impact force on a vertical and inclined slender pile - Theoretical and large-scale model investigations," *Coastal Engineering*, vol. 52, no. 5, pp. 435-462, 2005, doi: 10.1016/j.coastaleng.2004.12.008.

[29]. J. Song, S. H. So, and H. C. Lim, "Dynamic characteristics between waves and a floating cylindrical body connected to a tension-leg mooring cable placed in a simulated offshore environment," *International Journal of Naval Architecture and Ocean Engineering*, vol. 8, no. 4, pp. 375-385, 2016, doi: 10.1016/j.ijnaoe.2016.05.003.

[30]. B. Güzel and F. C. Korkmaz, "Experimental investigation of water entry of bodies with constant deadrise angles under hydrophobic effects," *Experiments in Fluids*, vol. 62, no. 5, pp. 107, 2021, doi: 10.1007/s00348-021-03202-x.

[31]. D. Zhou, E. S. Chan, and W. K. Melville, "Wave impact pressures on vertical cylinders," *Applied Ocean Research*, vol. 13, no. 5, pp. 220-234, 1991, doi: 10.1016/S0141-1187(05)80046-X.

[32]. C. Duez, C. Ybert, C. Clanet, and L. Bocquet, "Making A Splash With Water Repellency," *Nature Physics*, vol. 3, no. 3, pp. 180-183, 2007, doi: 10.1038/nphys545.

[33]. B. Güzel and F. C. Korkmaz, "Reducing Water Entry Impact Loads On Offshore Marine Structures By Forced Air Entrapment," *Ships Offshore Structures*, vol. 15, no. 9, pp. 942-952, 2020, doi: 10.1080/17445302.2019.1696534.

[34]. B. Güzel and F. C. Korkmaz, "Reducing Water Entry Impact Loads On Marine Structures By Surface Modification," *Brodogradnja*, vol. 71, no. 1, pp. 1-18, Mar. 2020, doi: 10.21278/brod71101.