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Technical note

EVALUATION OF WATER IMPACT FOR SYMMETRIC WEDGE BY EXPERIMENTAL AND NUMERICAL METHODS

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Evaluation of impact loads when a ship hull contacts the wave surface is one of the main issues for researchers who are going to design the structure of marine vehicles. In this paper, the results of experimental tests and numerical modeling of the distribution of pressure on different wedge-shaped models are reported and the effect of related parameters such as the deadrise angles, the weight and drop heights, is assessed. The output of analyses and the results can give appropriate approximations of the maximum impact pressures for the geometries that are similar to marine vehicle's hull sections to estimate the hydrodynamic impact loads in different sea-states. In addition, other effective parameters such as the impact speed, acceleration and water entry process can be used for evaluating the performance of such crafts.

Key words: symmetric wedge, hydrodynamic impact, impact pressure.

1. Introduction

Determination of hydrodynamic loads during impact is one of the challenging subjects for structural engineers who are trying to design optimum structures for high-speed crafts. These vessels should have enough structural strength to resist dynamic impact loads with minimum weight.

The complex fluid-structure interaction that occurs in the process of water entry phase should be evaluated by analyzing the impact pressures which act on the hull sections of the craft, but for simplifying the analysis, in the first step the evaluation of two-dimensional water impact of simple geometries such as wedges can be used to estimate the general hydrodynamic impact loads.

This paper describes an investigation into the water impact problem of symmetric wedges with different deadrise angles by numerical and experimental methods. Moreover, the hydrodynamic performance of the rigid wedges during impact such as the impact velocity, acceleration and the position of models during impact is assessed by numerical and experimental methods in this study. The results are expected to improve the accuracy of estimation of hydrodynamic loads in the design phase of high-speed crafts.

Von-Karman [1] was the first researcher to develop a theoretical method for impact pressure based on momentum theorem and the water added mass assumptions. He considered 2D sections of a seaplane during landing phase and derived simple formulas for impact pressure. This simple approach was continued by Wagner [2], Payne [3], Korobkin and Pokhnachov [4] with assuming the water splash effect on the wetted width of 2D sections.

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Dobrovolskaya [5] developed the first analytical solution for a solid wedge entering water vertically, but because it should be solved by complex numerical methods, it had some limitations. After 1990, the researches focused to find simple and practical methods to estimate hydrodynamic impact loads to use in design of marine vehicles. For example, Zhao and Faltinsen [6] and Mei *et al.* [7] proposed a linear approximation of water level for 2D geometries. Besides these theoretical and numerical methods, experimental tests had been conducted for similar problems and were used for validation of results. For example, Bisplinghoff and Doherty [8], Chuang [9-11], Ochi and Bonilla [12], Greenhow and Lin [13] conducted experimental tests on rigid bodies with consideration of different parameters such as deadrise angles, weight, impact velocity in an attempt to improve the accuracy of previous numerical results.

More recently, Lin and Ho [14] made experimental tests for impact of solid wedges in different heights and compared the results with numerical analyses based on the boundary element method. Zhao [15] proposed two methods for the analysis of water entry with non-linear simulation of Laplas equation and analytical solution of Wagner and validated the results with experimental tests of *30*° wedge. In addition, the studies of Ming-Chung Lin and Li-Der Shieh [16] presented experimental results on round hull's pressure distribution during water entry. These efforts were continued by Engle and Lewis [17] who compared the results of numerical and experimental methods for maximum pressure due to water impact for symmetrical wedge with different initial speed. These studies showed the validity area and accuracy of various methods. Faltinsen *et al.* [18] studied some important applications of water entry problem such as wetdeck slamming, green water, tank sloshing etc. In the same year, Wu *et al.* [19] conducted some experimental tests on wedges with 20 and 45 degree deadrise and compared the results with numerical data of complex method with analytical and BEM (Boundary Element Method) solutions. Yettou *et al.* [20] performed some experimental tests on different wedges for the calculation of the pressure coefficient with different weights and drop heights. It was shown that the deadrise angle has a more significant effect on the pressure in comparison with weight and drop height. In Sayeed *et al.* [21] evaluated the slamming force on wedge with *10*° deadrise and their results showed good correlation with Chaung's data.

Peng *et al.* [22] used drop test to measure the slamming loads on Trimaran crafts and investigated the distribution of impact pressure on them. Another study on water impact was conducted by Huarte *et al.* [23] which employed an experimental approach for the determination of characterization of flat plate impact loads. Kwon *et al.* [24] studied slamming loads based on experimental and numerical methods for analyzing the slamming problem with practical method. Finally, Shah *et al.* [25] used combined experimental and numerical approaches to determine the behavior of wedge performance during water-entry for aircraft ditching. The trend to investigate water entry is still ongoing.

In this paper, for symmetric solid wedges with deadrise of *15*°, *20*° and *30*°, the water entry process is modeled and numerical simulation is done and validated by experimental outputs. Based on the current results, estimation of hydrodynamic loads on 2D sections of typical high-speed crafts can be proposed which may be used in the design phase of marine vehicles.

2. Methodology

Numerical simulation of wedge sections was carried out and validated with experimental test results. The numerical analysis was made with ANSYS 17.1 software followed by the drop test experiments. A parametric study was carried out to determine the effect of parameters such as the impact speed, weight and deadrise angle on impact pressure. The specification of models is shown in Tab.1 and the basic geometries are illustrated in Fig.1

Table 1. Specification of models.

No.	Dead-rise angle (°)	Weight (kg)	Drop height (cm)
1	15	20, 26, 30	50, 75, 100
2	20		
3	30		

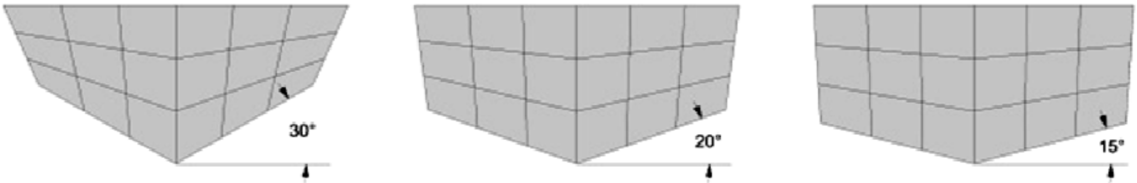


Fig.1. The geometry of models.

3. Numerical simulation

Modeling of the geometries was done for three models which are shown in Fig.1. Numerical analysis began when the wedges were in contact with the water surface. The simulation was considered for three deadrise angles with different weights that were dropped from *50*, *75* and *100 cm* and a fine mesh was used near the borders of the wedge and coarse ones for other areas. The positions of pressure sensors and the CG (Center of Gravity) of the models that were considered for tracking of wedge motion are shown in Fig.2

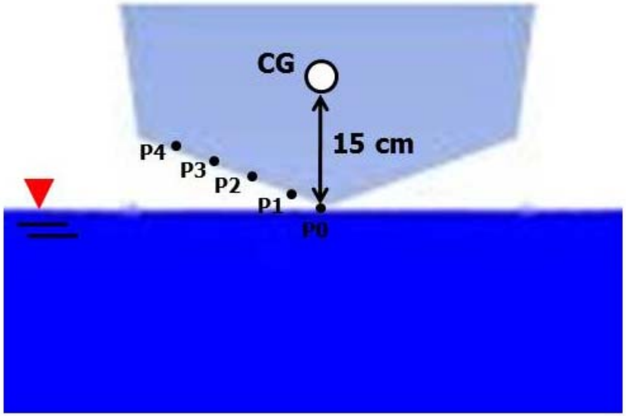
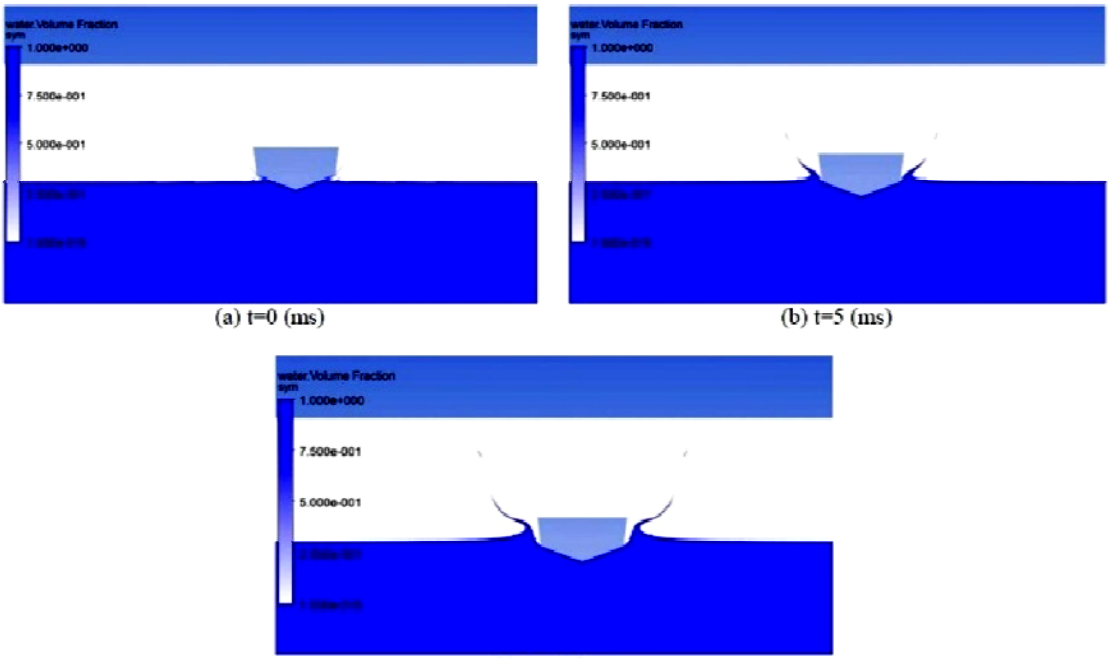


Fig.2. The position of pressure sensors and the CG of model.

Figure 3 shows the process of simulation for water entry of the *15*° wedge that was dropped from *100 cm*.



(a) t=0 (ms)

(b) t=5 (ms)

(c) t=10 (ms)

Fig.3. The process of simulation for water entry of *15*° wedge with drop height *100 cm*.

The time-histories of velocity and position of CG for simulation are shown in Figs 4 to 6. The period of effective impact time are shown in the figures. This time period can be used in the structural analysis as a time period during which the impact loads are acting on the structural elements.

During this period, because of the interaction between water and the wedges, the kinetic energy was reduced at a high rate, resulting in a high acceleration which leads to a considerable impact force experienced by the model. According to the figures, this impact force is exerted on the model over 10 msec. This behavior represents the phenomena in rough seas.

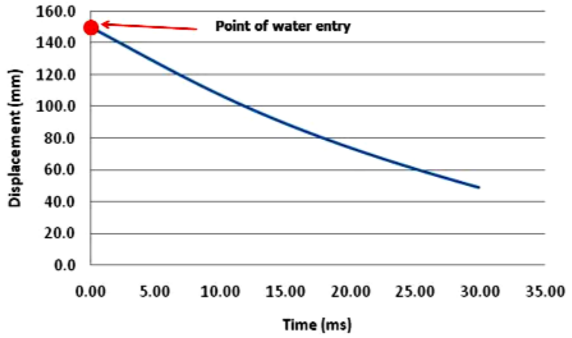


Fig.4. CG position-time history of *15*° wedge with drop height *100 cm.*

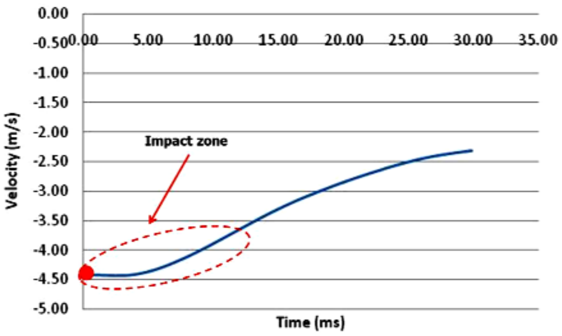


Fig.5. Velocity-time history of *15*° wedge with drop height *100 cm.*

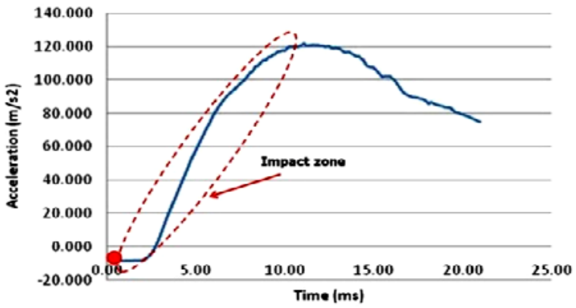


Fig.6. Acceleration-time history of *15*° wedge with drop height *100 cm.*

The behavior of the *15*° wedge is depicted in Fig.7 which is also an illustration of experimental tests.

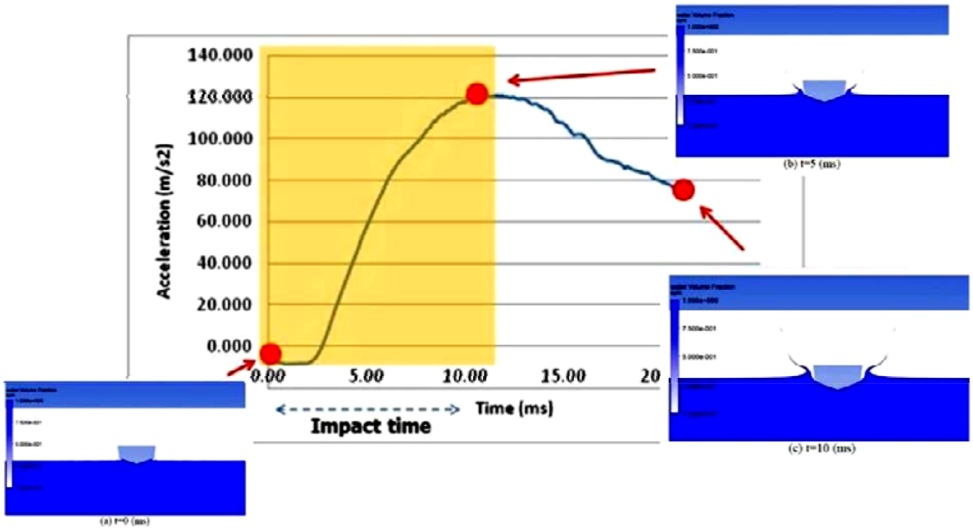


Fig.7. Acceleration-time history of *15*° wedge with drop height *100 cm*.

During the impact, as shown in Fig.7, the peak acceleration occurred when the water level reached the side of the model. This observation was reported before by Wagner [2], Mayo (1945) and recently by Shah *et al*. [25]. This point can be considered as a critical point for the analysis of the maximum impact load on the structure of marine vehicles in various sections.

The peak pressures of the models with various deadrise angles are shown in Fig.8. It can be observed that the maximum pressure for various deadrise angles decreased considerably with increasing the deadrise angle. The maximum impact pressure of *20*° model is about *40*% less than the value for *15*° model.

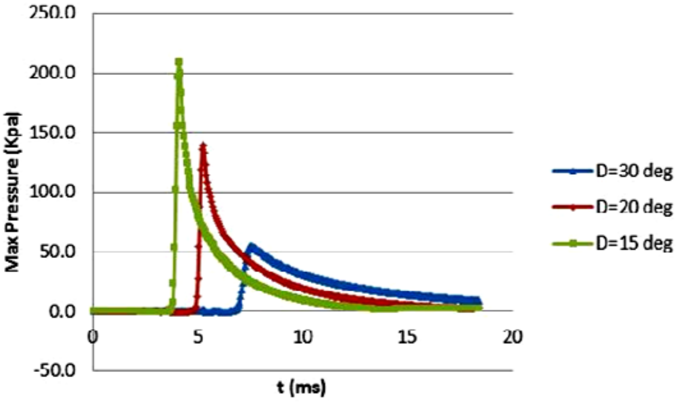


Fig.8. The peak pressure of the models with various deadrise angles at drop height *100 cm*.

The fluctuations of impact loads for different drop heights are shown in Fig.9 for *15*° deadrise. A higher drop height, as expected, leads to a higher kinematic energy and transfers a large momentum to the system. Therefore, the resultant impact force decreased when the drop height decreases. For example, it can be seen that for the drop height decreased by *25 cm*, the impact force decreased about *27*% from *100 cm* to *75 cm*. This difference was higher for decreasing the height from *75cm* to *50cm*.

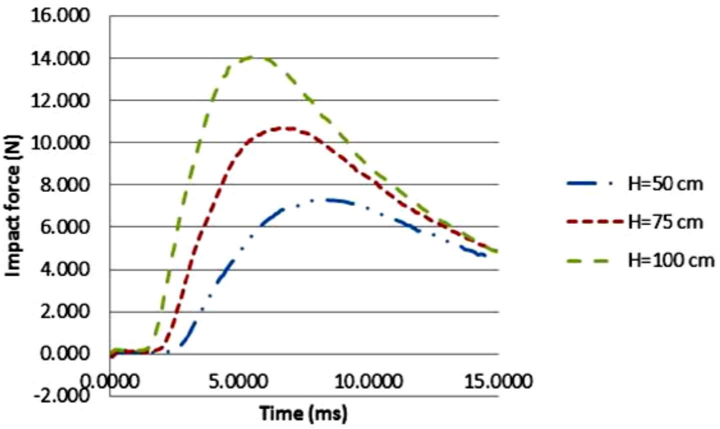


Fig.9. The fluctuation of impact load for different drop heights for *15*° deadrise.

The effect of model's weights on the impact force is shown in Fig.10 for the model with *15*° deadrise. This figure shows that the weight of different models has a negligible effect on the peak of impact loads compared to the effect of deadrise angle and the drop height.

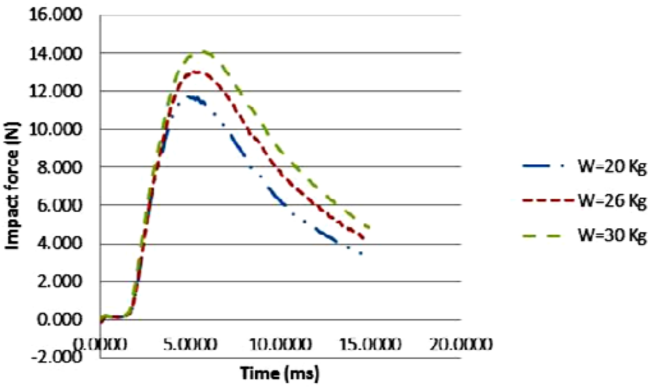


Fig.10. The effect of model's weight on the impact force for *15°* deadrise.

4. Experimental tests

For the experimental tests, rigid wedges were constructed with similar geometries as those simulated in numerical analysis. A special test rig was designed to constrain the motion in the vertical direction. The setup of the experimental test rig was reported in Nikfarjam *et al.* [26]. The models were dropped onto calm water surface from three different heights. Three pressure transducers were installed on one side of the wedges. These sensors can measure the pressure up to *1000* psi with accuracy range of *0.001* psi. The models were made of *4 mm* marine aluminum and were dropped vertically under the effect of gravity. Each test was repeated three times and the average of results was used as final data. When the wedge contacts the water surface, sensors can register the pressure changes over time. Table 2 shows the process of water entry for the *15°* wedge which was dropped from *100 cm*.

Table 2. The process of water entry for *15°* wedge dropped from *100 cm.*

Deadrise(°)	**time (ms)**		
	0	**5**	**10**
15			

The comparison of the effect of drop height on the maximum impact pressure for the model is shown in Fig.11

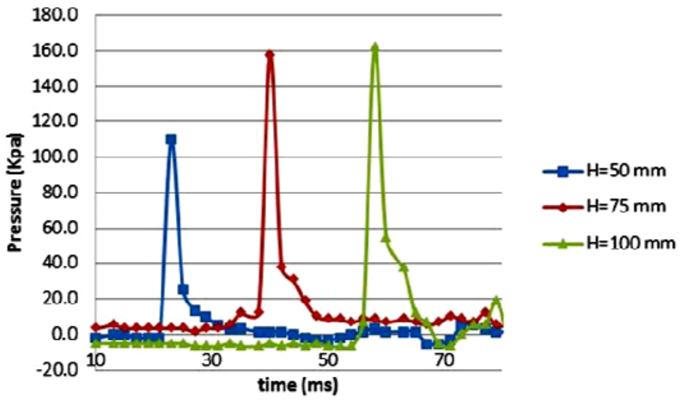


Fig.11. The effect of drop height on the maximum impact pressure for 15° wedge.

The peak pressures of the models with various deadrise angles are shown in Fig.12. The trend of variation of results is similar to Fig.8 but the maximum values are different.

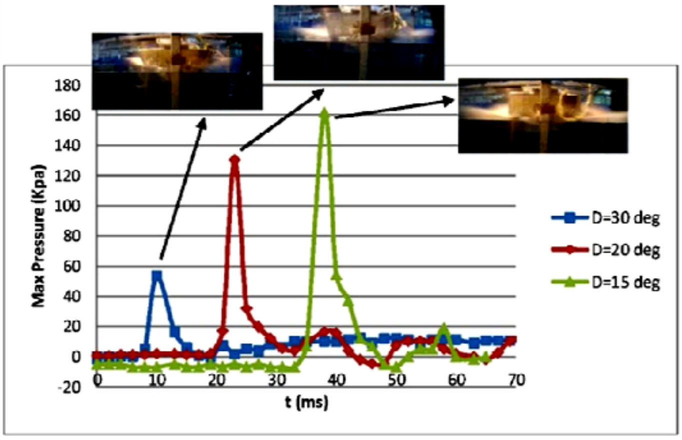


Fig.12. The peak pressure of the models with various deadrise angles.

For validation of the results of simulation, the comparison of peak pressure is shown in Fig.13.

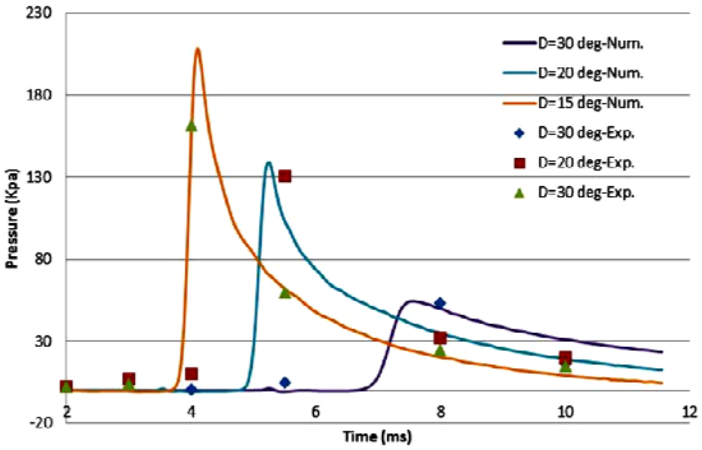


Fig.13. The comparison of peak pressure results for simulation and experiments.

For explanation of the difference between the results of the two approaches, a physical visualization of water level from numerical simulation is compared to that observed through the experimental tests in Fig.14 for *15°* wedge which was dropped from *100 cm*. It can be seen that the water level that was simulated in CFD is similar to that observed in the experiments, but the numerical simulation showed that the water level rises longer and faster along the side. This observation was reporter by Shah *et al.* [25] via their simulation by SPH (Smoothed-particle hydrodynamics) method.

The difference between the two observations due to longer length of spray area in the simulation shows that the mass of the fluid in the spray area in the experimental test has a lower velocity than the same particles in the numerical simulation. It can be predicted that the momentum of the water in the simulation has higher quantity compared to same momentum in the real conditions. In other words, it seems that the momentum that was transferred to the water by the wedges should be modeled accurately by the CFD method.

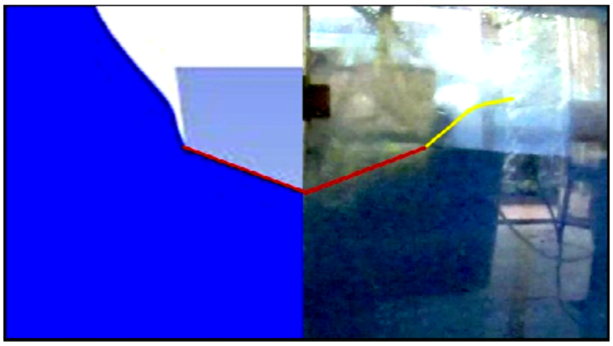


Fig.14. The comparison of water level from simulation and experimental tests for 15° wedge.

Meanwhile, the comparison of maximum pressure from the results of numerical simulations and experimental tests for different deadrise angles is depicted in Tab.3. All data were considered for the same weight. It can be seen that for the *15°* wedge the difference between results is about *29*%, but for higher angles the differences are relatively small. These conclusions are similar to those reported by Shah *et al.* (2015). In all cases, numerical results give over-predicted results. This over-prediction can be attributed to the uncertainties of impact phenomena which cannot be modeled by the CFD method, while the impact pressures were measured by accurate sensors in the experimental tests.

Table 3. The comparison of maximum pressure from numerical simulations and experiments.

	Deadrise (°)		
	15	**20**	**30**
Max P [kPa]-Num. simulation	*208.4*	*139.1*	*54.4*
Max P [kPa]-Exp. tests	*161.7*	*130.5*	*53.4*
Error (%)	*29*	*7*	*2*

Although differences were observed between the results of the two methods, the data showed good correlation and it means that the CFD method can adequately give a good approximation of the peak pressure and also simulation of impact event.

In the analysis of water-entry phenomenon, the evaluation of the pressure coefficient (*CP*) and dimensionless drop height (*Z*) was used to extend the results to the full scale cases. The pressure coefficient can be calculated according to Eq.(4.1) for different deadrise angles.

In Eq.(4.1), *P* is the maximum impact pressure at a desired point of measurement and *V* is the impact velocity. In Eq.(4.2), h is the vertical distance of point of measurement to the water level. The value of ρ and *t* are the water density and time, respectively.

$$C_P = \frac{P}{0.5 \times \rho \times V^2}, \tag{4.1}$$

$$Z = \frac{h}{V \times t}. \tag{4.2}$$

Figure 15 shows the effect of drop heights on the pressure coefficient for *30°* wedge. Three different heights were used (*H=50mm*, *H=75mm* and *H=100mm*). The results are compared with the experimental data of Zhao *et al.* [15] and it can be seen that the CP of the measured points showed a good correlation with the mentioned experimental data.

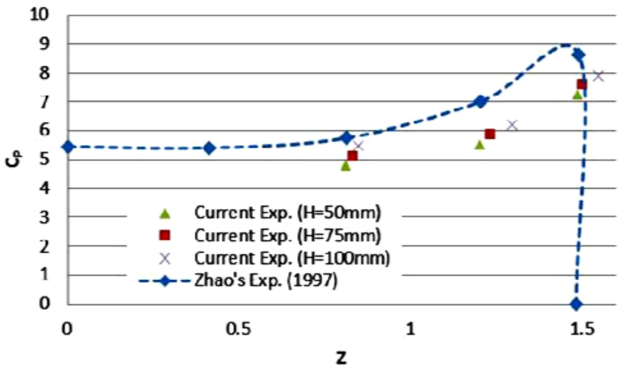


Fig.15. The pressure coefficient of the *30°* wedge compared with the experimental data of Zhao *et al.* [15].

The maximum pressure in all cases was located at the first sensor. It can be seen that the initial drop height does not affect the Cpmax and the measured data provide a good estimation for Cpmax. The differences might be due to the different assumption for the weight of the models. This is a simple method to estimate the local impact pressure on a hull with same deadrise angles during wave jumping.

Conclusions

The problem of wedge water entry has been assessed in this paper through experimental tests and numerical modeling. The models with different deadrise angles and weights were successfully simulated using the CFD method with ANSYS software. Peak pressures for the two approaches were compared and it was found that the results of simulation were over-estimated compared to experimental data. Therefore, it seems that the data for lower deadrise angles should be used with conservative consideration, but as a general approach, the numerical simulation results were accurate enough to use.

In the next step, water drop tests in the basin with calm water were conducted and the pressure data were measured and the process was captured with high-speed camera to compare the water level between numerical simulation and experimental tests. The observations showed that modeling of transferred momentum of dropped wedge was not as accurate as that which occurred in the experiments. Analysis of the data has yielded the following conclusions:

- based on numerical simulations, the deadrise angle is the main parameter that affects impact loads, resultant pressures and peak values;
- the weight of the model has a negligible effect on the impact loads;
- it was found that when the water level reached the side of dropped wedge, peak acceleration occurred, which can be used as a critical point for structural design;
- the comparison of peak pressure values obtained in numerical simulation and experimental tests showed various differences with decreasing rate when the deadrise angles were increased. Generally, the analysis of data showed that the results of simulation can be used as a good reference for peak pressures but more factors should be considered for the estimation of water level.

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