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Damage Process of High-piled Wharf Subjected to Underwater Explosion

Jinghan Liu[1,2], Ting Tang[2], Zhuobin Wei[2] and Lingfeng Li[1,2]

1. Naval University of Engineering, Wuhan 430033, Hubei, China
2. Naval Logistics Collage of PLA, Tianjin 300450, China
Email: 1226001717@qq.com

Abstract. In order to study the damage process of high-piled wharf subjected to underwater explosion, analysis model of high-piled wharf was established. The load characteristics of piles and panel of high-piled wharf were analysed during shock wave propagation and bubble pulse. The failure mode of wharf is basically completed in the first bubble pulse. The damage effect at the top of the pile is the most serious, the damage at the middle is slight, and the damage at the bottom is the weakest. Concrete damage occurs at the connection between pile and beam, beam and longitudinal beam. As the depth of explosive decreases, the damage effect of piles decreases and the damage effect of wharf superstructure increases. When the explosive explodes near the water surface, the wharf panel is damaged seriously and ultimately unusable.

1. Introduction
The high-piled wharf is one of the most common wharf structures in muddy coasts and estuaries. Underwater explosion is one of the main striking forms to high-piled wharf. It is significant to study the damage process of the high-piled wharf for improving the survivability on the design of high-piled wharf in wartime.

Numerical simulation is more efficient than field test for underwater explosion research. Rajendran R [1] used finite element software LS-DYNA to simulate the dynamic response of circular plate and square plate under underwater explosion. Schiffer [2] considering the cavitation and initial hydrostatic pressure, studied the response of structure subjected to shallow and deep water explosive, and then analysed the cavitation phenomenon and load distribution near composite plate by numerical methods. Based on LS-DYNA simulation, Cardoso [3] analysed and optimized the structural design of plates and shells to improve the protection capability. Flow field boundary has great influences on underwater explosion shock wave and bubble fluctuation.[4] Yan Qiushi [5] used numerical simulation software to analyse the damage effect of reinforced concrete single pile and obtained the anti-explosion area of single pile under specific depth. The study of damage mechanism and failure model of high-piled wharf lays a foundation for further research on anti-explosion performance of high-piled wharf.

2. Numerical Model
Based on the common harbour, the water depth of the harbour basin is 17m and the water bottom is saturated clay. The whole wharf is composed of standard structural sections. The piles, beams and slabs are all reinforced concrete structures. The superstructure is 26.5m wide and contains seven piles, including three vertical piles and two pairs of inclined piles. The distance between vertical pile and inclined pile is 4.5m, and the distance between inclined piles is 1.7m. The cross-sections for both

vertical and inclined piles are 600×600 mm. The length of the pile into the soil is 36 m and the length of pile in water is 17m.

The explosive, 117.45 kg TNT, is located between two vertical piles as shown in Figure 1-2. The depth of explosive is 8.5m. Considering the symmetry and calculation efficiency of the finite element model, only the piles near the explosive and the upper structure are established. The 1/2 finite element model is shown in Figure 3. The model includes: concrete, steel, water, soil and explosive. The Lagrange element is used for concrete and steel, and the Euler element is used for air, water, explosive and soil. The coupling between structure and fluid is defined by *Constrained_Lagrange_In_Solid. Concrete model is concrete_Damage_Rel3 model [6], considering the influence of deviator stress invariant on strength failure surface. The concrete strength of pile is 35.0 MPa, and the concrete strength of superstructure is 28.2 MPa, density is 2550 kg/m^3, Poisson's ratio is 0.2. Strain rate effect of concrete is set by the curve of dynamic load increasing coefficient. [7]

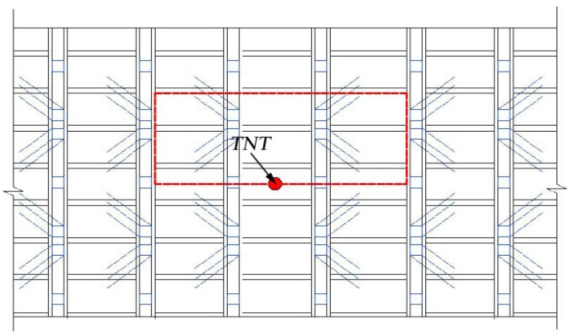

Figure 1. Overhead View

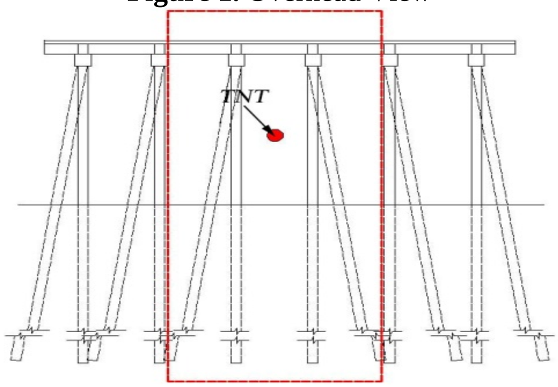

Figure 2. Main View

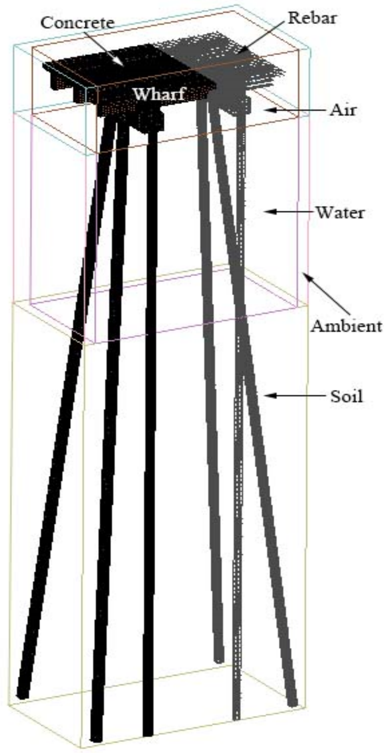

Figure 3. Finite Element Model

The steel model is Mat_Plastic_Kinematic, HRB335. Air is linear polynomial equation of state, C_0~C_6 are parameters of state equation and E is initial internal energy. Water is Gruneisen equation of state, C, S_1~S_3 are parameters of state equation and γ is Gruneisen constant. Explosive is JWL equation, A, B, ω, R_1, R_2 are parameters of state equation. Clay is linear elastic model, E is Elastic modulus and G is shear modulus. Detailed material parameters are shown in Tab 1.

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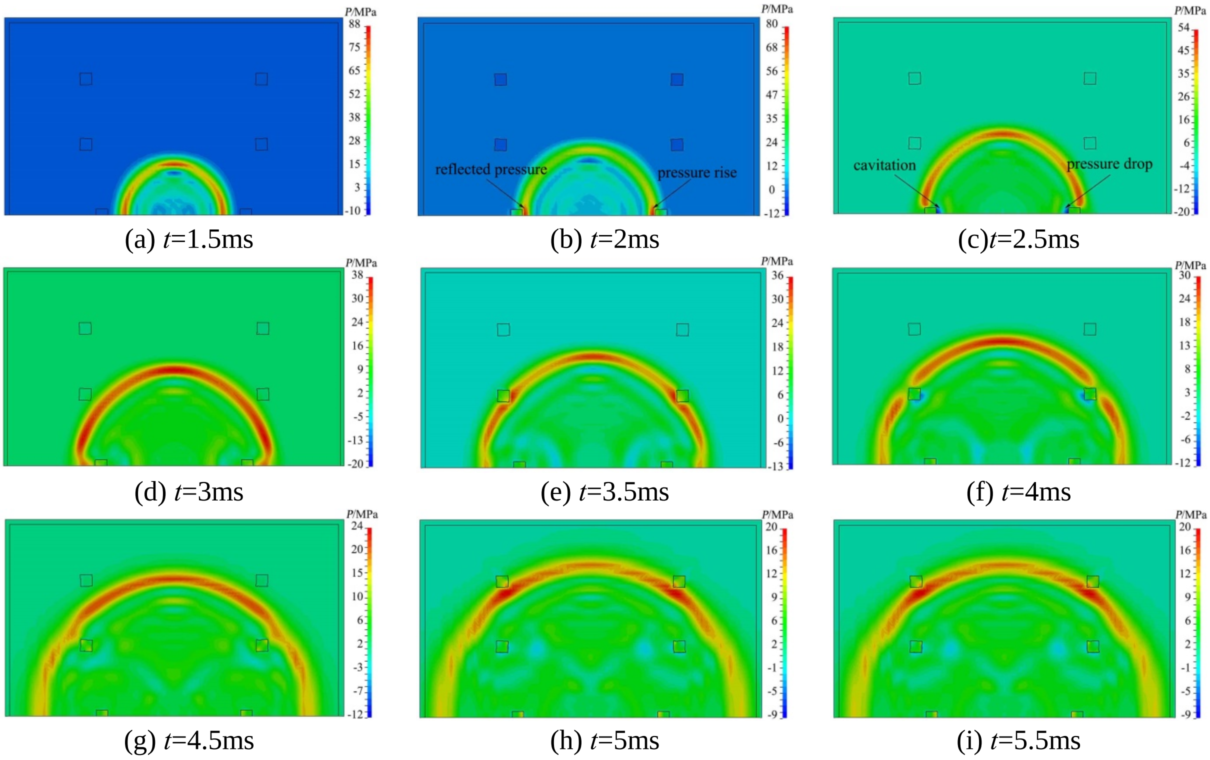
Table.1 Material Parameters of FEM Calculation Model

Material	ρ/(kg·m^{-3})	C_0-C_3	C_4	C_5	C_6	E/(J·kg^{-1})
Air	1.29	0	0.4	0.4	0	2.5×10^5
Material	ρ/(kg·m^{-3})	C	S_1	S_2	S_3	γ
Water	1000	1 480	2.56	-1.986	0.226 8	0.5
Material	ρ/(kg·m^{-3})	A/GPa	B/GPa	ω	R_1	R_2
TNT	1630	3.74×10^{11}	7.33×10^9	0.3	4.15	0.95
Material	ρ/(kg·m^{-3})	E/MPa	G/MPa			
Soil	1800	22.4	8			

3. Shock Wave Loading

As shown in Figure 4, the initial shock wave propagates spherically and reaches the vertical piles at t=2ms. Because the wave resistance ratio of the concrete is larger than that of the water, the shock wave reflects obviously near piles. During the shock wave passing through the vertical piles (t=2.5ms), the pressure in the front of the pile decreases sharply because the cavitation occurs. The reverse force loads on the piles. When t=3.5ms, the shock wave reaches the inclined piles. Because the inclined pile bears the shock wave load laterally, the reflection of the shock wave is weak and the attenuation of diffracted shock wave is not obvious. Shock wave completely bypasses six piles at t=6ms. It can be found that the reinforcement effect of vertical pile on shock wave is stronger than that of inclined pile and the attenuation of diffracted shock wave near inclined piles is less than that of vertical pile. Therefore, the vertical pile is subjected to stronger shock wave load in the shock wave stage.



(a) t=1.5ms (b) t=2ms (c)t=2.5ms
(d) t=3ms (e) t=3.5ms (f) t=4ms
(g) t=4.5ms (h) t=5ms (i) t=5.5ms

Figure 4. Propagation of Shock Wave around Piles

4. Bubble pulse

As shown in Figure 5, the bubble expands and extrudes the vertical piles at t=0.07s. The back of the vertical piles are damaged firstly, and then the bottom and top of the piles are damaged. The damage effect at the top of piles is stronger than that at the bottom of the piles because of the buffering effect of clay bottom. Bubble reaches the maximum volume at t=0.27s, then bubble shrinks and the pile is sucked by bubble. At the same time, bubble is affected by Bjerknes force of the piles. The bubble near the pile shrinks slowly and the upper and lower surfaces of bubble shrink fast. It gradually forms bubble jet pointing upward at t=0.62s. The jet breaks through the surface of bubble and forms toroidal bubble. Bubble surface near the piles does not completely shrink to form "tail" near the piles due to Bjerknes force. The toroidal bubble expands in the second bubble pulse process. During the second bubble pulse, the damage phenomenon of high-piled wharf basically remains unchanged.

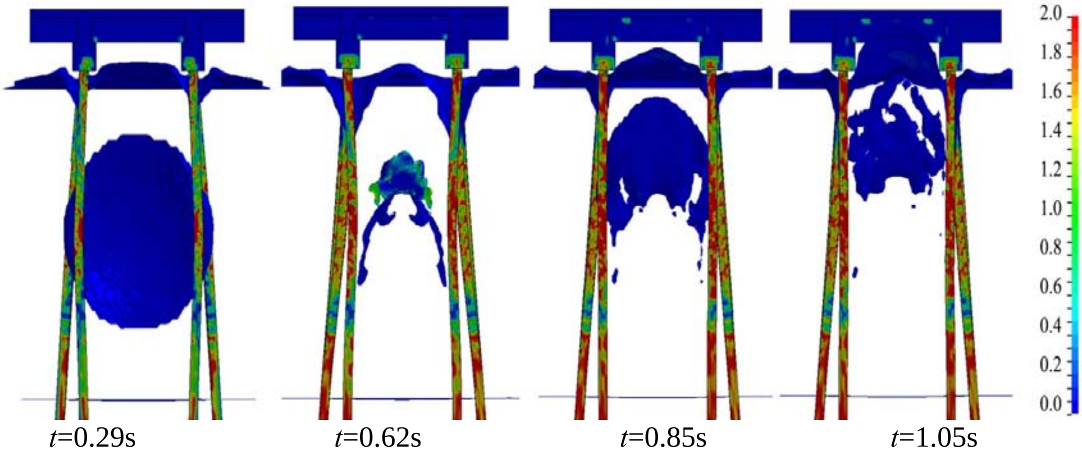


Figure 5. Bubble Pulse Process and the Damage Process of the Wharf

As shown in Figure 6, the first bubble pulse period of underwater explosion is 0.63s, and the maximum radius of bubble is 5.29m at t=0.29s, which is less than the theoretical radius, 6.11m. Piles hinder the expansion of bubble, and bubble collapses earlier in the second bubble pulse period. The maximum bubble radius in the second bubble pulse period reaches only 56.54% of the maximum radius in the first bubble pulse period. There are three peaks in bubble kinetic energy curve, which occur in the initial stage of underwater explosion and at two times of bubble jet. The kinetic energy of two bubble jets accounts for 16.26% and 12.47% of the initial bubble kinetic energy, respectively.

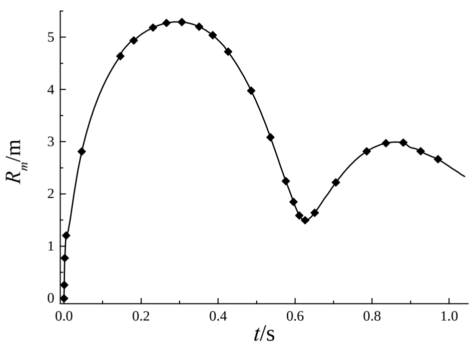


Figure 6. Radius-time of the Bubble

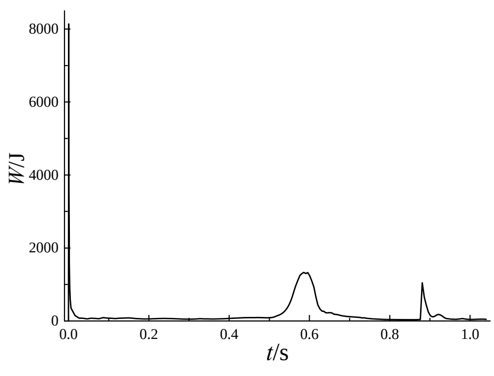
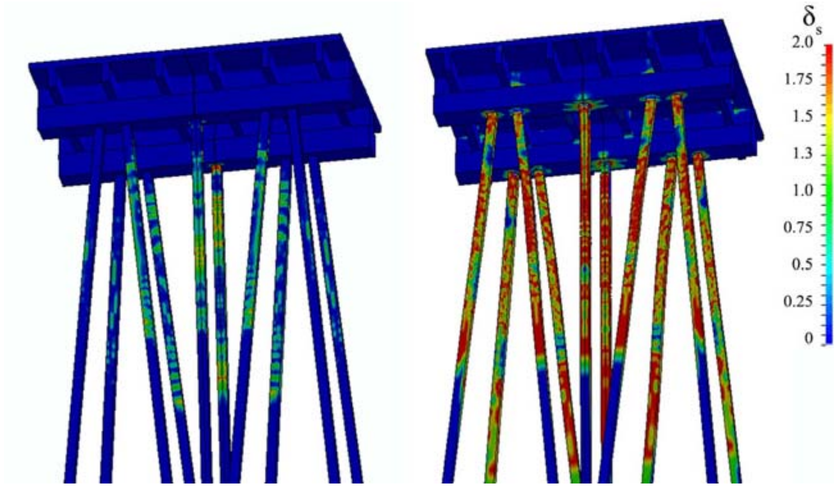


Figure 7. Kinetic Energy-time of the Bubble



(a) t=10ms (b) t=1.05s

Figure 8. The Damage Effect of High-piled Wharf

The Figure 8 shows the damage appearance of high-piled wharf subjected to shock wave loading and bubble pulse. The damage area is mainly at the top, middle and bottom of the piles, the damage of wharf superstructure is slight under shock wave loading. The failure mode of high-piled wharf is mainly formed during bubble pulse. The top and middle of piles are damaged most seriously. Concrete at the connection of piles and beams has been destroyed and failed, and slight damage occurs at the connection of beams and longitudinal beams.

5. Explosive depth

The Figure 9 shows the bubble pulse and the damage process of high-piled wharf when explosive depth is 1m. During the shock wave phase, the shock wave impulse to the pile body is slowed down due to the cut-off effect of water surface. Damage starts to occur in the back of the piles. Subsequently, there is damage effect at the connection of the piles and beams. During the bubble growth, the bubble expands in ellipsoid shape, and the bubble forms a conical water mound on the water surface due to the weak restraint effect of the water surface. As the water mound moves up, bubble directly loads on the wharf panel and longitudinal beam directly. The front face of wharf panel is compressed and the back face is pulled as a result of the bubble load. Because the tensile strength of concrete is far less than the compressive strength, the back of the panel is seriously damaged and cracks are formed in the centre of the panel at t=15ms. Damage effect occurs at the connections of longitudinal and cross beams, longitudinal beams and slabs. The continuous expansion of detonation products loads directly on the wharf panel. The damage area increases obviously in the connections of longitudinal beams, cross beams and wharf panel. After the concrete of the back panel fails, the wharf panel breaks and the steels of the slab are seriously deformed. The bubble collapse because of the wharf superstructure at t=200ms, the explosion product leaks out and turbulence occurs near the water surface. The damage effect of wharf panel is the most serious and the damage of piles decreases gradually as the distance of explosive increases.

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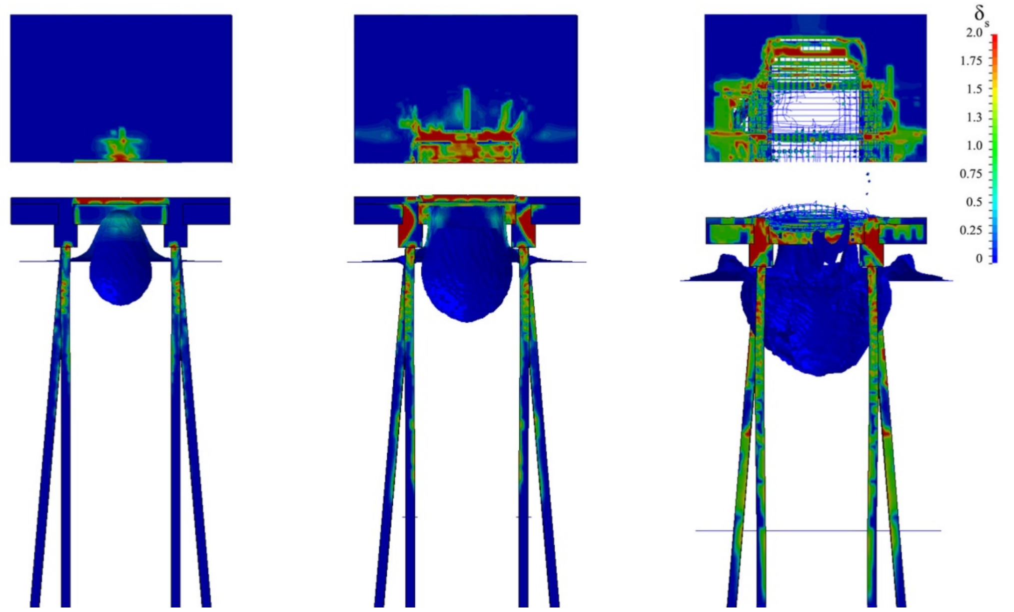
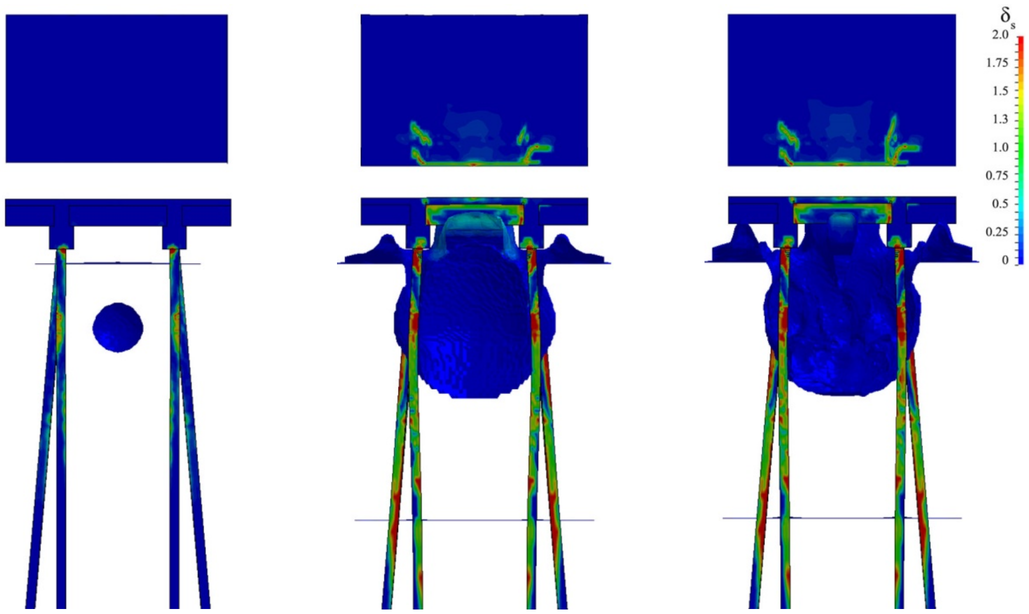


t=15ms *t*=40ms *t*=200ms

Figure 9. Bubble Pulse Process and the Damage Process of the Wharf (h=1m)

The Figure 10 shows the damage process of high-piled wharf when the depth of explosion is 4.5m. With the increase of explosive depth, the time of bubble forming water mound loading on the wharf panel is delayed. The transverse and oblique cracks are formed on the back of the panel at *t*=0.2s. The bubble breaks up because of the obstruction of the panel at *t*=0.3s. The damage effect of the panel and piles remain basically unchanged after bubble collapse. With the increase of explosive depth, the damage effect of piles increases and the damage effect of wharf panel, crossbeam and longitudinal beam decreases.



(a) *t*=0.1s (b) *t*=0.2s (c) *t*=0.3s

Figure 10. Bubble Pulse Process and the Damage Process of the Wharf (h=4m)

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6. Conclusions

In this paper the finite element model of high-piled wharf was established. The damage process of high-piled wharf and bubble pulse were researched. The results presented in this paper lead to the following conclusions.

(1) The damage areas are mainly in the top, middle and bottom of the piles subjected to shock wave loading. The piles are subjected to repeated loading due to the reflection and diffraction of shock wave. The vertical pile is subjected to stronger shock wave load than inclined pile.

(2) The damage appearance of the high-piled wharf basically remains unchanged at the end of the first bubble pulse. The bubble impulsive is the main contributor to the damage of high-piled wharf.

(3) The damage effect of piles decreases and the damage effect of superstructure increases as the depth of explosive decreases. The wharf panel beaks by bubble impulse when the explosive explodes near the water surface.

7. References

[1] Rajendran R. *Numerical simulation of response of plane plates subjected to uniform primary shock loading of non-contact underwater explosion*. 2009. *Materials & Design*. **30**:1000-1007.

[2] Schiffer A, Tagarielli V L. *The response of circular composite plates to underwater blast: Experiments and modelling*. 2015. *Journal of Fluids & Structures*. **52**:130-144.

[3] Cardoso D, Valente R, Paulo R M F. *Numerical simulation and design of extruded integrally stiffened panels (ISP) for aeronautic applications subjected to blast loading*: 2013 *Sensitivity analyses to different stiffener configurations*.

[4] LIU Jinghan, TANG Ting, WEI Zhuobin, etc. *Pressure characteristics of shallow water explosion near the rigid column.2019 Chinese Journal of High Pressure Physics.* **33**(5): 055104.

[5] YAN Qiushi, NING Suyu, DU Xiuli, et al. *Damage effect for a typical reinforced concrete pile under the near field explosion in water*. 2019. *Journal of Beijing University of technology.* **45**(02):55-61.

[6] Tu Z, Lu Y. *Evaluation of typical concrete material models used in hydrocodes for high dynamic response simulations.* 2009. *International Journal of Impact Engineering*. **36**(1):132-146.

[7] Malvar LJ, Ross CA. *Review of strain rate effects for concrete in tension*. 1998. *ACI Materials Journal* **95**(6): 735-739.