ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20231117152820

Original scientific paper
Received: 2023-11-17, Accepted: 2023-12-01

Comparison of Maximum Peak Pressures of Free Underwater Explosion by Numerical Modeling and Empirical Expressions

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Abstract: The article compares the results of empirical expressions for the maximum peak pressures of an underwater explosion and numerical models made in hydrocode software LS-DYNA. Spherical charge of 136.08 kg TNT explosive was chosen and observed distance was up to 15 m. An overview of empirical expressions is given and the results according to several authors are compared. The Cole expression was chosen as a reference for comparison. For the purpose of the numerical modelling, the influence of the size of the finite elements of the explosive, the size and shape of the volume of water and the size of the finite elements of water was examined. The size of the finite elements of the medium (water) was shown to be the most significant parameter that affects the magnitude of the pressure results, and recommendations for modelling were given.

Keywords: empirical expressions; maximum peak pressure; numerical modelling; underwater explosion

1 INTRODUCTION

Underwater structures, such as maritime, river and hydrotechnical structures and infrastructure are potential targets of terrorist attacks. Their demolition can result in the interruption of supply lines and communications, as well as material damage and human casualties. The construction of underwater structures resistant to the action of an underwater explosion, intentional or unintentional, contributes to the safety of the community.

Explosives are conditionally stable, and after initiation, they convert to a stable state through a chemical reaction [1] [2]. The explosion creates a temperature of about 3000 °C, a pressure of about 5000 MPa and an increase in the initial volume up to 1000 times [1, 3]. The high pressure generates a shock wave, the speed of which, after a few milliseconds, decreases to the speed of sound in water (1500 m/s) [4, 5]. After the shock wave, the gaseous products of the detonation form a gas bubble, which expands under high pressure and temperature [4, 6]. The gas bubble expands, while the pressure in it drops, and then contracts, which is repeated several times, which is called gas bubble pulsation [7, 8].

Significant experimental research cannot be carried out in laboratory conditions because the scaling law cannot be applied to an underwater explosion [1]. Therefore, experimental research must be carried out in realistic conditions, which requires the engagement of significant material resources and specialized human resources, along with certain risks. Pressure measurement is very complex, and the shock wave propagates according to the sound wave theory [1]. Pressure magnitude, in real conditions, depend on salinity, in seawater, hydrostatic pressure, water stream, and temperature distribution has a special influence. Differences in water temperature cause bending of the wave, and the potential creation of sound channels, shadows and reverberation.

Available experimental and results obtained using empirical expressions are limited, and at some distances from the centre of the explosion have deviations of up to 50% [1]. Solving the differential equations, which describe the underwater explosion, is complex even for simple models. Numerical modelling of the underwater explosion and verification of the obtained numerical results on experiments is imposed as the only way to solve this task. Numerical underwater explosion modelling research is described in this paper.

2 EMPIRICAL EXPRESSIONS FOR DETERMINING MAXIMUM PRESSURES OF UNDERWATER EXPLOSIONS

In the literature, there are several empirical expressions from different authors for the calculation of the parameters of an underwater explosion in an unbounded medium. It should certainly be pointed out that most of these terms were created based on the terms proposed by Cole [1]. Based on numerous experiments, Cole [1] determined the empirical correlation of the maximum pressure, the distance from the centre of the explosion, and the amount of explosives for the spherical shape of the charge:

$$P_\mathrm{m} = k\left(\frac{W^{\frac{1}{3}}}{R}\right)^{\alpha}, \tag{1}$$

where P_m is the maximum pressure, k and α coefficients depending on the type of explosive, W is the mass of the explosive and R is the distance from the centre of the explosion. For TNT and its density 1.52 g/cm^3, Eq. (1) is:

$$P_\mathrm{m} = 52.39\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} \quad \text{(MPa)} \tag{2}$$

Alternatively, the author for close distances $R_0 < R < 6R_0$ gives the expression:

$$P_{\mathrm{m}} = 38.29 \frac{W^{\frac{1}{3}}}{R} \mathrm{e}^{0.1086 \frac{W^{\frac{1}{3}}}{R}} \quad \text{(MPa)} \tag{3}$$

Where R_0 is the radius of the sphere of the explosive charge. Zamyshlyayev i Yakovlev [9, 10] propose the following expressions for the maximum pressure depending on the dimensionless distance $\frac{R}{R_0}$:

$$P_{\mathrm{m}} = \left\{ \begin{array}{ll} 45\left(\frac{W^{\frac{1}{3}}}{R}\right) & 6 < \frac{R}{R_0} < 12 \\ 53.3\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} & 12 < \frac{R}{R_0} < 240 \end{array} \right\} \text{(MPa)} \tag{4}$$

Vranješ [6] also proposes two expressions for the maximum pressure, depending on the dimensionless scaled distance:

$$P_{\mathrm{m}} = \left\{ \begin{array}{ll} 53.3\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.92} & 1 < \frac{R}{R_0} < 5 \\ 53.3\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} & 7 < \frac{R}{R_0} < 1000 \end{array} \right\} \text{(MPa)} \tag{5}$$

Furthermore, some authors in the Cole equation, where the maximum pressure depends on the mass of the explosive and the standoff distance at the point being measure, proposed different coefficients, for TNT, expressed Mousem [11], as (Reid, 1996):

$$P_{\mathrm{m}} = 52.12\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.18} \quad \text{(MPa)} \tag{6}$$

and Moradi [12], as (Rajendran and Narasimhan 2006):

$$P_{\mathrm{m}} = 52.16\left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} \quad \text{(MPa)} \tag{7}$$

Based on the Eq. (1), various authors proposed other values of the coefficients k and α [1] or determining the maximum pressure from the explosion of a spherical TNT charge (Tab. 1).

Table 1 Coefficients k and α [1, 11-14]

	Cole	Mousem	Ozarmut	Moradi	Grzadiela
k	52.39	52.12	52.40	52.16	52.30
α	1.13	1.18	1.13	1.13	1.13

Fig. 1 and Tab. 2 show the results of maximum pressures as a function of the distance from the centre of the charge obtained according to the expressions of Cole, Mousem and Moradi. Since the results are very similar along the entire observed front, the empirical expression Cole (1) and adopted coefficients k = 52.39 and α = 1.13 will be used for further analysis and comparison of pressures.

However, the maximum pressure obtained by the Vranješ expression, at a distance of 1 m, is significantly higher from other maximum pressure values.

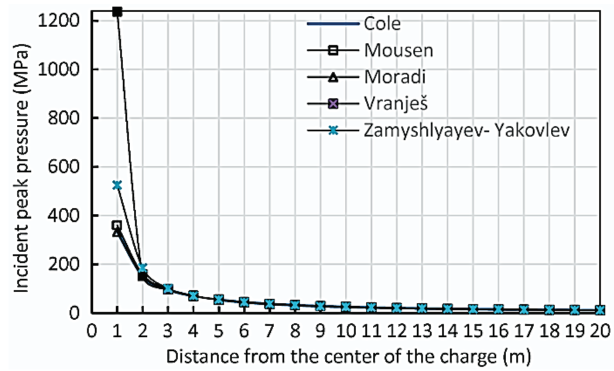

Figure 1 Incident peak pressures with distance

Table 2 Incident peak pressures with distance

Distance (m)	Cole	Mousem	Moradi	Vranješ	Zamyshlyayev-Yakovlev
	Pressure (MPa)				
1	333.4	360.0	331.9	1237.0	524.9
2	152.3	158.9	151.7	155.0	185.6
3	96.3	98.5	95.9	98.0	101.0
4	69.6	70.1	69.3	70.8	70.8
5	54.1	53.9	53.9	55.0	55.0
6	44.0	43.5	43.8	44.8	44.8
7	37.0	36.2	36.8	37.6	37.6
8	31.8	30.9	31.7	32.4	32.4
9	27.8	26.9	27.7	28.3	28.3
10	24.7	23.8	24.6	25.1	25.1
11	22.2	21.3	22.1	22.6	22.6
12	20.1	19.2	20.0	20.5	20.5
13	18.4	17.5	18.3	18.7	18.7
14	16.9	16.0	16.8	17.2	17.2
15	15.6	14.7	15.6	15.9	15.9
16	14.5	13.7	14.5	14.8	14.8
17	13.6	12.7	13.5	13.8	13.8
18	12.7	11.9	12.7	12.9	12.9
19	12.0	11.2	11.9	12.2	12.2
20	11.3	10.5	11.2	11.5	11.5

3 NUMERICAL SIMULATION OF A FREE UNDERWATER EXPLOSION

3.1 Numerical Models

Numerical models were created in hydrocode software LS DYNA [15, 16]. The models consist of two parts, water and explosive. Water is modeled as a fluid by Gruneisen's equations of state, without calculation of deviatoric stresses

[17]. Gruneisen's equations of state describes the relationship between pressure, density of water and its specific internal energy. For compressed water ($\mu > 0$), the pressure is:

$$p=\frac{\rho_0 C^2 \mu\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu-\frac{\alpha}{2}\mu^2\right]}{\left[1-(S_1-1)\mu-S_2\frac{\mu^2}{\mu+1}-S_2\frac{\mu^3}{(\mu+1)^2}\right]}+(\lambda_0+\alpha\mu)e \quad (8)$$

where ρ_0 is the initial density of the medium, ρ is the density of the medium, C is the speed of sound in water, γ_0 is the Gruneisen coefficient, S_1, S_2 and S_3 are dimensionless coefficients, α is the correction coefficient and

$$\mu=\frac{\rho}{\rho_0}-1 \quad (9)$$

Specific internal energy of water is calculated according to the expression:

$$e=\frac{\rho g h+P_0}{\rho\gamma_0} \quad (10)$$

where h is the water depth, and P_0 atmospheric pressure. Tab. 3 shows the parameters of the water equation of state.

Table 3 Parameters of the Gruneisen equation of state [13]

ρ_0 (g/cm^3)	C (m/s)	S_1	S_2	S_3	γ_0	α
1.0	1480	1.75	0.0	0.0	0.28	0

The TNT explosive is modelled by the Jones – Wilkins – Lee (JWL) equation of state [17]:

$$p=A\left(1-\frac{\omega}{R_1\chi}\right)e^{-R_1\chi}+B\left(1-\frac{\omega}{R_2\chi}\right)e^{-R_2\chi}+\frac{\omega e}{\chi} \quad (11)$$

where p is the pressure, χ is the relative volume, e is the specific internal energy and A, B, R_1, R_2, ω, are the constants of the equation of state determined experimentally. Tab. 4 gives the values of the parameters of the JWL equation of state.

Table 4 Parameters of the JWL equation of state [13]

ρ_0 (g/cm^3)	A (kPa)	B (kPa)	R_1	R_2	ω
1.63	3.71×10^8	3.23×10^6	4.15	0.95	0.3

3.2 Multidimensional Parametric Analysis

3.2.1 The Influence of the Shape of the Observed Volume of Water

To obtain reliable results, it is necessary to carry out a multidimensional parametric analysis of how the size of the observed volume of water, the size of the finite elements of the explosive and the medium (water) affects the pressure results. The investigation of the underwater explosion was carried out on numerical models with the assumptions of homogeneity and isotropicity of water and explosive, as well as uniform temperature and salinity for seawater, where hydrostatic pressure was neglected. Computing time depends on the size of the model, therefore the aim is to reduce the model as much as possible. First, it will be examined whether the pressure results are affected by the reduction of the volume and shape of the observed water volume, using the spatial symmetry and permeable boundaries of the medium. The researched model is symmetrical around all three planes, and this fact was used in the modeling so that mirror boundary conditions were applied on the external SPH (smoothed particle hydrodynamics) surfaces, and the FEM nodes were constrained. Defining the type of outer model boundaries plays a critical role in the simulation and the resulting pressures. The outer boundary of the model can be defined as a no-slip and no-penetration boundary, in which case the velocity, pressure and temperature values of the particles remain preserved in the model. When modeling a free explosion in a water, as in this case, an outflow boundary was used where the particles retain their direction and speed at the boundary itself.

Water volumes with dimensions of 20×20×20 m (model 1), 20×5×5 m (model 2), 20×4×4 m (model 3), 20×3×3 m (model 4) and 20×2×2 m (model 5) were investigated, where the amount of explosives in the form of a sphere was 136.08 kg and was discretized into 1512 finite elements (Fig. 2). The size of the finite elements of water was fixed in all models and was 25×25×25 cm.

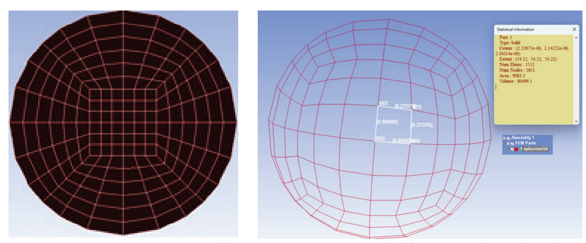

Figure 2 Discretization of explosives, section (left) and surface (right)

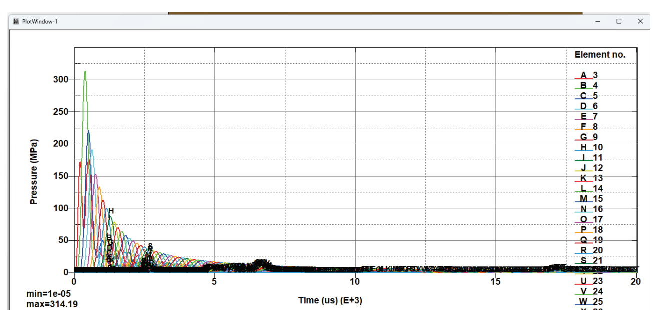

Figure 3 Example of the output results in graphic form

After the numerical processing of the previously adopted model, numerical results are obtained for various values of certain parameters of the underwater explosion in nodes, elements, etc. (Fig. 3). In addition to the possibility of viewing changes in individual parameters over time, the output data enables viewing the animation of the underwater explosion in shades of different colors with different values of the selected parameters.

For pressure, the change in pressure value over time is obtained, which is equal on the entire finite element. Along with the pressure change diagram, the maximum pressure value is displayed, and other values can be read at certain times.

Fig. 4 shows the maximum pressures at distances of 1.5 m, 10 m, 13.5 m, 15 m and 20 m for all the models. Negligible deviations of maximum pressures are visible at distances from 15 m to 20 m where the pressures are very small.

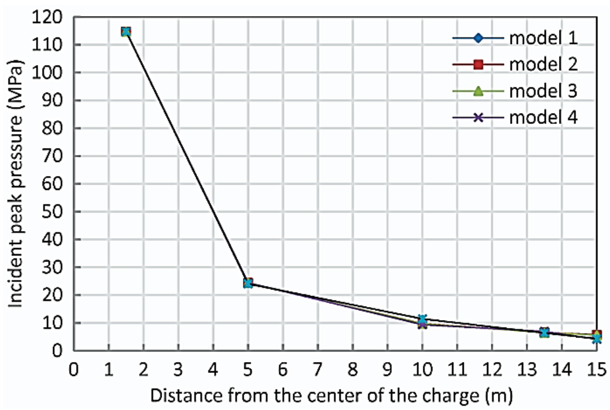

Figure 4 Incident peak pressures for different dimensions of the observed volume of water

By comparing the numerical results for these five models of different volumes, it can be concluded that the shape and size of the volume of the model has very little effect on the results of the maximum pressures. This fact will be used to minimize the calculation time since it increases exponentially with the volume of the space and the number of the finite elements.

3.2.2 Influence of the Size of the Finite Elements of the Explosive

As already mentioned, the TNT explosive in the form of a sphere with a radius of 27 cm and a mass of 136.08 kg was selected. To investigate the influence of the size of the finite elements of explosive, three sizes of finite elements were chosen, where the sphere was discretized into 3818, 7001 and 12097 elements. Tab. 5 shows the maximum pressures at a distance of 1.5 m from the centre of the explosion, where the volume of water is discretized into Hexahedral elements with edges of 10 cm, 12.5 cm, 20 cm and 25 cm. As is to be expected, the size of the maximum pressures depends on the fineness of the discretization of the water volume, but the size of the finite elements of the explosive has almost no influence on them. Therefore, the fineness of the explosive discretization does not have to be considered during further analyses. Anyway, in the further analysis the model with 12907 finite elements of the explosive will be used, because their number does not affect either the pressure results or the duration of the calculation, so any of the mentioned models could be chosen.

Table 5 Incident peak pressures at a distance of 1.5 m from the centre of the explosion depending on the size of the finite elements of the explosive

Number of finite elements of explosive	Size of the finite elements of water			
	10 cm	12.5 cm	20 cm	25 cm
	Pressure [MPa]			
3818	200.44	177.65	133.67	114.66
7001	200.43	177.23	133.80	114.73
12097	200.41	176.81	134.48	114.76

3.2.3 The Influence of the Size of the Finite Elements of Water

The dependence of the size of the finite elements of water and maximum pressures was tested on the water volume model 20×5×5 m. The finite elements of water are 10 cm (model 6), 12.5 cm (model 7), 20 cm (model 8) and 25 cm (model 9), with discretization of explosives into 12907 elements.

Fig. 5 and Tab. 6 compare the maximum pressure values obtained by the empirical Eq. (1) and four pressure diagrams, based on the obtained numerical results, at distances from 1.5, 2.0 to 20.0 m, with a step of 1 m.

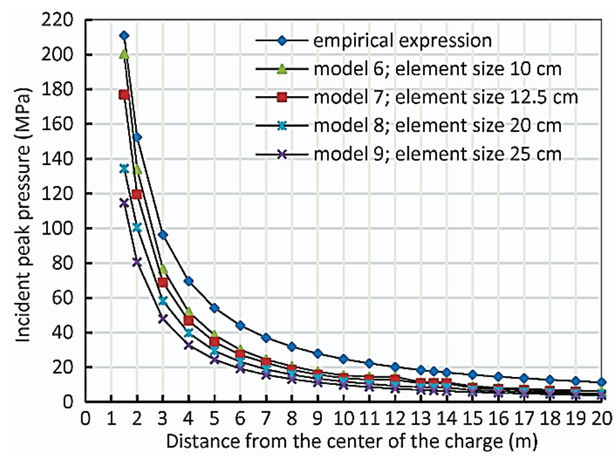

Figure 5 Incident peak pressures for different dimensions of finite elements of water

The largest deviations in the value of the maximum pressures from the results obtained by the empirical expression are shown by the model with the size of the finite elements of water 25×25×25 cm. By reducing the size of the finite elements, deviations are also reduced, but even for elements of size 10×10×10 cm, these deviations are relatively large, especially in the interval between 3 m and 12 m. In the area of very high pressures at a distance of up to 3 m, these deviations are within the permissible limits for engineering purposes only for elements of 10 cm size, but all other results show a drastic underestimation of the maximum pressure values. It can be concluded that these sizes of finite elements are not suitable for application.

By further reducing the size of the finite elements of water, the results converge to empirical values. Fig. 6 compares the maximum pressure values for the size of the finite elements of water (3×3×3 cm, 5×5×5 cm and 6×6×6 cm). The diagram shows how by reducing the size of the finite elements of water, the pressure results approach the empirical ones.

Table 6 Incident peak pressures for different dimensions of finite elements of water

R (m)	Size of the finite elements of water								
	Emp. expr.	10 cm		12.5 cm		20 cm		25 cm	
	p (MPa)	p (MPa)	Δ (%)	p (MPa)	Δ (%)	p (MPa)	Δ (%)	p (MPa)	Δ (%)
1.5	210.9	200.4	4.9	176.8	16.1	134.4	36.2	114.7	45.5
2.0	152.3	134.1	11.9	119.6	21.4	100.5	34.0	80.5	47.1
3.0	96.3	76.7	20.3	68.9	28.4	58.2	39.5	47.8	50.3
4.0	69.6	51.9	25.4	46.7	32.8	39.8	42.8	32.7	52.9
5.0	54.1	38.4	28.9	34.6	35.9	29.4	45.6	24.3	54.9
6.0	44.0	30.0	31.6	27.1	38.4	23.0	47.6	19.1	56.5
7.0	36.9	24.4	33.9	22.5	39.0	18.7	49.3	15.5	57.8
8.0	31.8	20.4	35.6	18.4	41.9	15.7	50.6	13.0	58.9
9.0	27.8	17.4	37.2	15.7	43.3	13.4	51.8	11.1	59.8
10.0	24.7	15.2	38.3	13.7	44.4	11.6	52.7	9.7	60.6
11.0	22.2	14.4	34.8	12.7	42.7	10.2	53.6	8.5	61.3
12.0	20.1	14.4	28.0	12.7	36.8	9.1	54.3	7.6	61.9
13.0	18.3	11.3	38.3	10.7	41.6	8.2	55.0	6.8	62.5
13.5	17.6	11.3	35.6	10.7	39.1	8.2	53.3	6.5	62.8
14.0	16.9	11.3	32.9	10.7	36.5	8.2	51.4	6.2	63.0
15.0	15.6	8.9	43.0	8.0	48.6	6.8	56.2	5.7	63.5
16.0	14.5	8.1	43.7	7.3	49.2	6.2	56.7	5.2	64.0
17.0	13.5	7.5	44.5	6.8	49.8	5.8	57.2	4.8	64.5
18.0	12.7	6.9	45.0	6.3	50.3	5.3	57.6	4.4	65.0
19.0	11.9	6.5	45.5	5.8	50.7	4.9	58.3	4.1	65.64
20.0	11.3	6.1	45.8	5.5	50.8	4.7	58.4	3.8	66.30

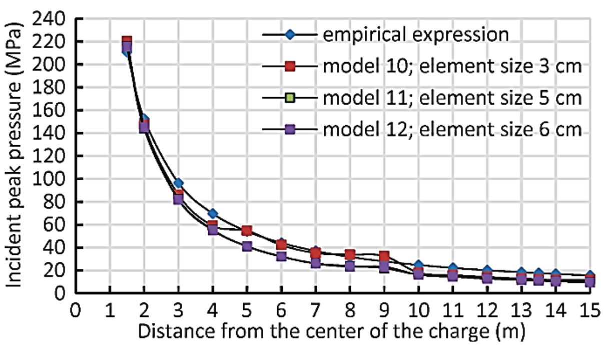

Figure 6 Incident peak pressures for different sizes of finite elements of water

Table 7 Incident peak pressures at distances up to 15 m from the centre of the explosion depending on the size of the finite elements of the explosive

R (m)	Size of the finite elements of water						
	Emp. expr.	3 cm		5 cm		6 cm	
	p (MPa)	p (MPa)	Δ (%)	p (MPa)	Δ (%)	p (MPa)	Δ (%)
1.5	210.9	220.5	–4.5	216.0	–2.4	215.4	–2.1
2.0	152.4	146.9	3.6	143.8	5.6	145.0	4.8
3.0	96.4	86.0	10.8	82.3	14.6	81.7	15.2
4.0	69.6	59.0	15.2	55.5	20.3	55.1	20.9
5.0	54.1	54.6	–1.0	40.9	24.4	41.1	24.1
6.0	44.0	42.1	4.4	32.1	27.1	32.1	27.0
7.0	37.0	35.2	4.7	26.1	29.4	26.0	29.8
8.0	31.8	33.8	–6.1	23.9	24.8	23.2	27.0
9.0	27.9	32.6	–6.9	21.9	21.4	23.2	16.8
10.0	24.7	18.0	27.1	16.3	34.0	16.2	34.4
11.0	22.2	15.9	28.4	14.4	35.1	14.4	35.3
12.0	20.1	14.2	29.3	12.9	36.1	12.8	36.5
13.0	18.4	12.8	30.2	11.6	37.0	11.5	37.6
13.5	17.6	12.2	30.8	11.0	37.5	10.9	37.9
14.0	16.9	11.6	31.3	10.5	37.8	10.4	38.2
15.0	15.6	11.6	25.7	9.7	38.1	9.6	38.8

The smallest deviation of the numerical results from the results obtained using the empirical expression is for the model with finite elements of water 3×3×3 cm. From Tab. 7 it can be seen that all three sizes of finite elements gave good results in areas of very high pressures, at a distance of up to 2 m, but by increasing the distance, up to 10 m, finite elements of size 3 cm give the best results. In the area of low pressures, over a distance of 10 m, the differences range from 31 % for the smallest finite elements to 38 % for the largest.

The results show a strong dependence of the pressure results on the size of the finite elements of water. Regardless of the increasing capacities of computers, numerical models are very complex and the same challenge always arises, how to reduce the amount of input data and obtain acceptable results. For engineering needs and the area of high pressures (up to $20R$), the acceptable accuracy is 15 %, but for areas of low pressures (over $20R$), the criteria can be relaxed [18].

4 CONCLUSIONS

Researching the impact of underwater explosions is very complicated and associated with risks and the commitment of significant resources. Most of these experiments are conducted under the auspices of the military services, so many results are not publicly available. Therefore, the best way to assess the impact on naval structures is numerical simulation, which, on the other hand, also hides numerous insecurities. In addition, numerical simulations require significant computing resources and computing time. For example, the calculation of a model with a volume of water 20×20×20 m and finite elements 25×25×25 cm takes about 16 minutes, and a model with a volume of water 20×2×2 m and finite elements 3×3×3 cm takes more than 10 hours (Intel Celeron P4600 processor and 4 GB DDR3). This article compares conventional empirical expressions with numerical results in order to optimize the ratio of computer time investment to the accuracy of the results.

The main parameter of the effect of an underwater explosion on underwater structures is the maximum pressure on the wave front. It mostly depends on the size and shape of the explosive charge and the distance from the centre of the explosion. Since the numerical modelling of an underwater explosion is a complex procedure that requires powerful computer resources, the explosion model should be made so that the calculation time is within reasonable limits, and the results are accurate enough for engineering needs. This research showed that the observed volume of water can be reduced to the form of an elongated cube with permeable boundaries and that this does not significantly affect the results. Also, the density of the mesh of finite elements of the explosive has no influence, but the results of maximum pressures largely depend on the size of the finite elements of water. Hexahedral finite elements of water 10 cm and larger have been shown to be unsuitable, and with further size reduction the pressures converge. For areas of very high pressures (up to $20R$), finite elements of size 3 cm proved to be a reasonable compromise between calculation time and accuracy, and for areas of low pressures finite elements of size up to 6 cm can be applied.

5 REFERENCES

[1] Cole, R. H. (1948). *Underwater explosions*. Princeton University Press. https://doi.org/10.5962/bhl.title.48411

[2] Božić, B. (1998). *Miniranje u rudarstvu, graditeljstvu i geotehnici*. Geotehnički fakultet Varaždin, Varaždin. (in Croatian)

[3] Pleše, M. (2008). *Fizika i kemija eksplozivnih tvari*. MORH·OS RH·HVU, Zagreb. (in Croatian)

[4] Mousum, M. H. (2018). Numerical Analysis of Immersed steel & Composite Cylindrical Shell Structures Submitted to UNDEX. *Master Thesis*, Institute Catholique d'Arte et Metries (ICAM), Nantes, France.

[5] Panaa, I. F., Puicaa, C., Goga, D. A., & Nuta, I. (2015), Numerical Studies Regarding Underwater Detonation. *Conference Emerging Markets Queries in Finance and Business 2014, EMQFB 2014*, 24-25 October 2014, Bucharest, Romania, *Procedia Economics and Finance, 32*, 946-951. https://doi.org/10.1016/S2212-5671(15)01552-X

[6] Vranješ, B. (1973). *Podvodna eksplozija*. Mornarički školski centar, Split. (in Croatian)

[7] Constanzo, F. A. (2010). *Underwater Explosion Phenomena and shock Physics*. Naval Surface Warfare Centre Carderock Division. Jacksonville, Florida, USA.

[8] Pritchtt, J. W. (1971). *An evaluation of various theoretical models for underwater explosion bubble pulsation*. Information Research Ashociates, Berkely Marina, California, USA. https://doi.org/10.21236/AD0737271

[9] Zamyshlyayev, B. V. & Yakovlev, S. Yu. (1973). *Dynamic loads in underwater explosion*. National technical information service. Naval Intelligence Support Centre, Washington, D. C.

[10] Chun-liang, X., Shan, Y., Jian, T., Zhi-Ping, T., Li. Y., & Xin-quan, W. (2017). Numerical simulation of bubble pulsation generated by deep water explosion. *Proceedings of the 7th International Conference on Mechanics and Materials in Design*, Albufeira/Portugal 11-15 June 2017. Editors Silva J.F. Gomes and S.A. Meguid., Publ. INEGI/FEUP.

[11] Mousum, M. H. (2015). *Numerical Analysis of Immersed Steel & Composite Cylindrical Shell Structures Submitted to UNDEX*. Developed at Institute Catholique d'Arts et Metiers (ICAM), Nantes France.

[12] Ozarmut, B., Ruhl, A., Hennings, B., Nommensen, O., & Paul, A. (2019). Fluid-Composite Structure-Interaction in Underwater Shock Simulations. https://api.semanticscholar.org/CorpusID:197675435

[13] Moradi, M., Aghajanzadeh, S. M., & Mirzabozorg, H., & Alimohammadi, Mahsa. (2018). Underwater explosion and its effects on nonlinear behavior of an arch dam. *Coupled Systems Mechanics, 7*, 333-352. https://doi.org/10.12989/csm.2018.7.3.333

[14] Grzadziela, A. (2011). Ship impact modelling of underwater explosion. *Journal of KONES Powertrain of Transport, 18*(2), 145-152.

[15] LS – PrePost, (2016). *User's Manual*, Dyna, An advanced pre and postprocessor and model editor for LS-DYNA, Livermore Software Technology Corporation, Livermore, California.

[16] Olovsson, L., Souli, M., & Do, I. (2003). LS DYNA – ALE capabilities (Arbitrary-Lagrangian-Eulerian) Fluid structure Interaction Modelling, Livermore Software Technology Corporation, Livermore.

[17] Working Group (20189. *LS Dyna Keyword user's manual*. Volume II, Material Models, LS Dyna R11, Livermore Software Technology Corporation, Livermore, California.

[18] Draganić, H. & Varevac, D. (2018). Analysis of Blast Wave Parameters Depending on Air Mesh Size. *Shock and Vibration, 2018*. https://doi.org/10.1155/2018/3157457

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