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OPTIMIZATION OF ABOVE-GROUND CYLINDRICAL REINFORCED CONCRETE TANKS UNDER BLAST LOADING CONSIDERING FLUID-STRUCTURE INTERACTION EFFECTS USING THE PSO ALGORITHM

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Abstract: Above-ground storage tanks are significantly more vulnerable to damage from blast loading compared to bury or semi-buried concrete and steel tanks, primarily due to their exposed nature. To accurately assess the real behavior of above-ground tanks, it is essential to account for fluid-structure interaction (FSI) effects. Accordingly, in this study, 24 finite element models of cylindrical reinforced concrete tanks were developed in ABAQUS software and subjected to blast loading, incorporating FSI effects. The key variables considered include explosive mass, explosive distance, fluid fill level, tank wall height, and mesh size. The investigated responses encompass circumferential (hoop) stress and radial displacement. The design constraints were set as maximum allowable hoop stress (30MPa) and maximum displacement (20mm). The optimal tank was designed using C30 concrete and steel with a yield strength of 400 MPa. The tank dimensions were 15m in height and 33.85m in diameter. The explosive mass and explosive distance were set at 1000kg and 10m, respectively. The objective function was to minimize the tank weight while simultaneously satisfying the stress and displacement constraints. Using the Particle Swarm Optimization (PSO) algorithm, the minimum weight of the cylindrical reinforced concrete tank was determined to be 23933kN, which was achieved after approximately 25 iterations.

Keywords: Cylindrical Reinforced Concrete Tanks, Blast Load, Hoop Stress, Maximum Displacement, Optimization, PSO Algorithm

ОПТИМИЗАЦИЯ НАДЗЕМНЫХ ЦИЛИНДРИЧЕСКИХ ЖЕЛЕЗОБЕТОННЫХ РЕЗЕРВУАРОВ ПРИ ВЗРЫВНОЙ НАГРУЗКЕ С УЧЕТОМ ЭФФЕКТОВ ВЗАИМОДЕЙСТВИЯ ЖИДКОСТИ и КОНСТРУКЦИИ С ИСПОЛЬЗОВАНИЕМ АЛГОРИТМА PSO

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Аннотация. Наземные резервуары для хранения жидкостей характеризуются существенно более высокой уязвимостью к воздействию взрывных нагрузок по сравнению с заглублёнными и полузаглублёнными бетонными и стальными резервуарами, что обусловлено их открытым расположением. Для адекватной оценки напряжённо-деформированного состояния наземных резервуаров необходимо учитывать эффекты взаимодействия жидкости и конструкции (Fluid–Structure Interaction, FSI). В связи с этим в программном комплексе ABAQUS были разработаны 24 конечно-элементные модели цилиндрических железобетонных резервуаров, подвергаемых воздействию взрывной нагрузки с учётом FSI-эффектов. В качестве варьируемых параметров рассматривались масса взрывчатого вещества, расстояние до эпицентра взрыва, уровень заполнения резервуара жидкостью, высота стенки резервуара и размер конечных элементов расчётной сетки. В качестве исследуемых параметров отклика анализировались кольцевые (обручные) напряжения и радиальные перемещения конструкции. Проектные ограничения были заданы в виде максимально допустимого кольцевого напряжения 30 МПа и предельно допустимого перемещения 20 мм. Оптимальная конструкция резервуара была разработана с использованием бетона класса C30 и арматурной стали с пределом текучести 400 МПа. Геометрические параметры резервуара составили 15 м по высоте и 33,85 м по диаметру. Масса заряда взрывчатого вещества и расстояние до объекта были приняты равными 1000 кг и 10 м соответственно. В качестве целевой функции рассматривалась минимизация массы резервуара при одновременном соблюдении ограничений по прочности и деформативности. По результатам оптимизации с использованием алгоритма роя частиц (Particle Swarm Optimization, PSO) установлено, что минимальный вес цилиндрического железобетонного резервуара составляет 23 933 кН. Достижение оптимального решения было обеспечено приблизительно после 25 итераций алгоритма.

Ключевые слова: цилиндрический железобетонный резервуар; взрывная нагрузка; кольцевые напряжения; радиальное перемещение; оптимизация конструкций; алгоритм PSO

INTRODUCTION

Storage tanks are crucial structures for fluid containment in transmission networks, typically featuring fixed plan and elevation geometries. Their design and analysis account for inflow rates, site geotechnical conditions, and static/dynamic loading. Therefore, a precise investigation of tank behavior under blast loading is essential. A key aspect of analyzing such structures involves evaluating the effects of fluid-structure interaction in response to dynamic forces. For this purpose, the fluid (water) is assumed to be a continuous, incompressible, and irrational medium. Within the tank domain, the equations of motion are based on the governing differential equation for hydrodynamic wave propagation and the corresponding boundary conditions, which is the Laplace equation [1].

The seismic response of liquid storage tanks has been extensively studied by numerous researchers. Early studies in this field assumed rigid tank walls and considered both linear and nonlinear fluid behavior. Pioneers in this area were Jacobsen [2] and Housner [3], who investigated hydrodynamic pressure effects in tanks subjected to horizontal excitation. Jacobsen focused his studies on cylindrical tanks with rigid walls, while Housner modeled rigid cylindrical and rectangular tank systems in a manner practical for civil engineers. In Housner's model, the fluid pressure is divided into an impulsive component due to the part of the fluid accelerating with the wall and a convective component resulting from fluid sloshing. Subsequently, Epstein provided a series of equations and tables, assuming the convective component acts in the upper part of the fluid, to determine maximum seismic forces [4]. Later, Haroun and Housner, using the finite element method, boundary solutions, and computer programs, presented a new model of the tank-fluid system, considering not only the fundamental $\cos\theta$ mode but also higher-order $cosn\theta$ modes [5]. Veletsos then modeled the impulsive components of rigid and flexible wall tanks by substituting a pseudo-acceleration function for ground acceleration, followed by Ramerathoffer who proposed a design procedure for tanks considering both seismic components [6].

As observed, most existing research has considered earthquake forces as the dynamic effect on fluid storage tanks. However, such structures may also be subjected to other loadings, such as blast waves. The analysis of blast loading effects on structures began in the 1960s. In 1959, the U.S. Army published a manual titled "Structures to Resist the Effects of Accidental Explosions." A revised edition published in 1990 has been widely used by military and non-military organizations for the design of structures to prevent blast propagation and protect personnel and equipment [7]. Subsequently, numerous numerical and experimental studies were conducted on the effects of blast on various structures, including fluid storage tanks [8, 9]. Among these, research by Wang et al. demonstrated that a tank designed for seismic forces has lower resistance to blast, resulting from increased internal energy and reduced external work when adopting constrained boundary conditions [10]. Mittal researched the dynamic analysis of liquid storage tanks under blast using a combined Eulerian-Lagrangian formulation, showing that stresses increase with higher fluid fill level, decreased distance from the blast center, and increased height-to-radius ratio of the tank [11]. Li et al. investigated blast overpressure generated inside and outside groups of tanks. They provided methods for calculating internal and external pressures considering various spacing's between tanks [12, 13]. Zheng et al., using numerical methods, presented the stress and deformation in a gas tank subjected to a TNT explosive blast load [14]. Hu and Zhao modeled the effect of blast on a small-scale tank in FLUENT software and compared it with experimental specimens [15]. Peyman Safa conducted a nonlinear dynamic numerical analysis on ground-based floating roof tanks under blast loading for 30 different blast scenarios [16]. The obtained results indicated that the examined tank shells are vulnerable to some blast loading scenarios and would suffer damage based on the failure criteria of the API 650 standard. Yasseri, through experimental studies, proposed a relationship for obtaining the external blast pressure distribution around vertical pressure tanks [17]. The results of this research are applicable to tanks with heights smaller than their diameters. The numerical study by Wang and Zhou on a water tank under blast loading showed that water can mitigate the tank's blast response [18]. Alipour and colleagues, in their research, investigated the effects of explosive distance, charge height above ground, explosive mass, tank geometry, internal fluid condition, and internal fluid pressure distribution on both cylindrical and cubic reinforced concrete tanks with an equivalent cross-sectional area of 900 m², considering fluid-structure interaction effects [19, 20, 21]. Hosseini et al. in a study, increasing soil density was found to intensify pressure and stress on buried pipes under blast loading, whereas low-density soil acts as a damper, reducing pipe damage. Using the ALE method in LS-DYNA, parametric analysis showed that soil with lower density better mitigates explosion effects on concrete pipes [22].

MATERIALS AND METHODS

This study aims to perform a sensitivity analysis of parameters affecting hoop stress in above-ground cylindrical reinforced concrete tanks subjected to blast loading using the Monte Carlo simulation method. All studied responses are calculated and recorded at control points. In this research, control points are defined along the tank's peripheral surface at three elevation levels: bottom, mid-height, and top of the tank wall. The soil stiffness is assumed to be infinite in this study, effectively neglecting soil-structure interaction effects. (Figure 1) shows the geometric parameters of the cylindrical tank. The studied variables are as follows:

Explosive Mass: The loading in this study is of the blast type. One of the key factors influencing damage to the structure is the magnitude of the blast force. Explosive mass is one of the variables studied. Therefore, two values of TNT equivalent explosive mass are used: 500 kg and 1000 kg.

Explosive Distance: Another variable is the distance from the explosive charge to the tank. The closer the blast location is to the structure, the higher the likelihood of damage. The distances considered in this study are 10 m and 25 m. Internal Fluid Condition: To investigate fluid-structure interaction effects, the tank's behavior can be analyzed for three conditions: empty, half-full, and full. Tank Height: Given the nature of blast loading, which acts as compressive waves on the tank's external wall, a larger loaded surface area inevitably leads to greater effects. Therefore, tank height, which directly increases the loaded surface area, is studied as a variable.

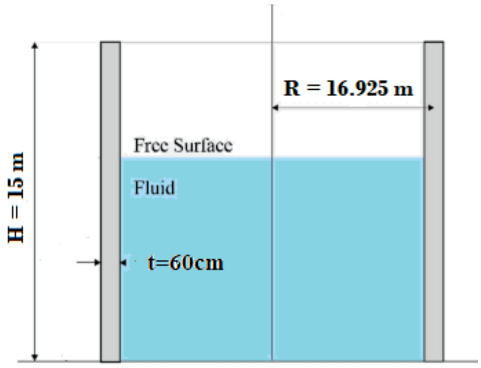

Figure 1. Geometric parameters of the cylindrical tank under study

Scaling Laws

The characteristics of a blast wave depend on the energy released from the explosive material and the propagation medium. These properties can be measured under controlled laboratory conditions and serve as a basis for obtaining information about other explosions using blast scaling laws. In blast loading, scaling blast wave properties is a common practice, and several methods have been proposed for estimating blast waves. Using scaling laws based on experimental results, the properties of a blast wave from any desired charge weight and distance can be estimated, assuming a perfect gas and neglecting gravity and viscosity; however, these laws are not suitable for very strong shock waves or distances very close to the explosion source. The Henrych scaling method used in this study for designing cylindrical reinforced concrete tanks is described below. According to Henrych's scaling laws, if a charge weight W (kg of TNT) detonates at a distance R from a structure, the peak incident overpressure P_{so} can be calculated from the following equations:

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (1)$$

$$P_{so} = \begin{cases} \frac{14.072}{Z} + \frac{5.54}{Z^2} + \frac{0.357}{Z^3} + \frac{0.000625}{Z^4} & 0.05 \leq Z < 0.3 \\ \frac{6.194}{Z} + \frac{0.326}{Z^2} + \frac{2.132}{Z^3} & 0.3 \leq Z < 1 \\ \frac{6.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} & 1 \leq Z < 10 \end{cases} \quad (2)$$

Where Z is the scaled distance.

Preliminary Design of the Cylindrical Reinforced Concrete Tank

In this section, a cylindrical reinforced concrete tank was designed based on the initial problem parameters. Table 1 presents the primary specifications used for the tank design.

Table 1. Initial problem specifications for the design of the cylindrical reinforced concrete tank

Parameter	Value
Total tank height	15 m
Outer diameter of the cylindrical tank base	33.85 m
Concrete class and compressive strength	C30 / 30 MPa
Unit weight of concrete	25 kN/m³
Yield strength of reinforcement steel	400 MPa
Fluid height inside the tank	7.5 m
Unit weight of fluid	10 kN/m³
Mass of explosive charge	1000 kg
Explosive distance of explosive from the tank	25 m

Based on the specifications in Table 1 and the provisions of Publication No. 123, the cylindrical reinforced concrete tank was designed as detailed in Table 2.

Table 2. Preliminary Design of the Cylindrical Reinforced Concrete Tank

Design Tensile Force	Design Bending Moment	Slab Reinforcement	Vertical Reinforcement	Horizontal Reinforcement	Slab Thickness	Wall Thickness
1523 kN/m	844 $kN.m/m$	Φ 16 @ 150mm	Φ25 @100mm	Φ20 @ 100mm	400mm	600mm

Modeling the Tank and Fluid under Blast Loading

The modeling procedure for all studied models in this research was similar and consistent. The differences between models were solely in numerical values, geometric parameters, and research variables. Therefore, this section presents the general modeling procedure for one of the studied models. The first step in the modeling process is creating the required parts. In this study, according to the variables under investigation, three parts were modeled: the tank, the water, and the reinforcements (vertical and circumferential). Concrete elements are of type S4R, water elements are of type AC3D8R, and reinforcement elements are of type T3D2. After creating all three parts, the materials for water, concrete, and steel are defined and assigned to the created parts.

The water density is taken as $1 \times 10^{-6}\ kg/mm^3$ and the water viscosity is set to 0.001. To define the fluid behavior, the Us-Up equations (Mie-Grüneisen equation of state) are used. For this purpose, the speed of sound $C_0 = 1480000\ mm/s$ the slope coefficient of the Us-Up curve $s = 1.79$ and the Grüneisen coefficient $\Gamma_0 = 0.5$ are defined. For the concrete tank, concrete with grade C30 is used, with a unit weight of $2.4 \times 10^{-6}\ kg/mm^3$ a Poisson's ratio of 0.2 and an elasticity modulus of 23.5GPa. To define the plastic properties and damaged behavior of concrete, the parameters related to the Concrete Damaged Plasticity model were considered according to Tables 3 and 4.

Table 3. Parameters for Concrete Damaged Plasticity Behavior

Eccentricity	Dilation Angle (°)	f_{b0}/f_{c0}	Eccentricity	Dilation Angle (°)
0.0001	0.67	1.16	0.1	30

Table 4. Compressive and Tensile Behavior of Concrete in ABAQUS Software

	Compressive Stress (MPa)	Plastic Strain	Tensile Stress (MPa)	Plastic Strain
1	11.25	0.0000	2.80	0.0000
2	18.75	0.0000	2.10	0.0001
3	22.50	0.0000	1.40	0.0002
4	25.00	0.0002	0.70	0.0003
5	23.75	0.0005	0.00	0.0004
6	21.25	0.0010		
7	17.50	0.0020		
8	12.50	0.0030		
9	10.00	0.0040		

Steel is used to model the reinforcements in concrete. The elastic properties of steel, including unit weight, Poisson's ratio, and elasticity modulus are$7.85 \times 10^{-6}\ kg/mm^3$, 0.3 and 210GPa respectively. Since blast loads (as impulsive loads) typically induce extremely high strain rates in the range of 100 to 10,000 s^{-1}, they alter the mechanical properties of materials and the expected mechanisms in the structure. According to Table 5, the plastic properties of steel are defined using the Johnson-Cook hardening model to account for strain rate effects on stress. According to Equation (3), stress in the Johnson-Cook model is defined as a function of plastic strain, strain rate, and temperature. This feature can be readily defined in ABAQUS software.

Table 5. Johnson-Cook Model Parameters for Steel Plastic Behavior.

Parameters	Value
A (MPa)	360
B (MPa)	635
n	1.03
m	0.114
Melting temperature (K)	1500
Transition temperature (K)	298
C	0.075
Epsilon dot zero	1

$$\sigma = (A + B\varepsilon^n)(1 + C.\,Ln\varepsilon^*)(1 - T^{*m}) \qquad (3)$$

Where ε^* is the dimensionless plastic strain rate relative to the reference strain rate, and $\dot{\varepsilon}$ is the plastic strain rate; T^* is the homologous temperature; A is the initial yield strength of steel at a reference plastic strain rate $\dot{\varepsilon} = 1/s$ and temperature of $298\ K$; B and n simulate the strain-rate-independent hardening behavior of steel; C represents the strain-rate-dependent hardening behavior; and m is the thermal softening coefficient, obtained from mechanical tests for steel and equal to 0.114. After assigning materials to the parts, all parts are assembled, and the charge weight and explosive distance are defined using the ConWep method. Accordingly, the desired points are defined as reference points using the Offset from point option, and subsequently, the charge weight is defined. It should be noted that the tank base is modeled with fixed supports and is fully constrained.

VALIDATION

To ensure the accuracy of the modeling performed in this study, the results presented here were verified against those from a reputable reference. For this purpose, one of the models examined by Moghadam et al. was simulated, and the obtained results were compared with those presented in that reference. It is worth noting that previous studies have compared different numerical modeling methods for applying blast loads to water storage tanks to assess their accuracy. In this section, the blast loading on the tank is applied in ABAQUS software and compared with the numerical modeling method proposed by Moghadam et al. for evaluation. Steel water tanks with various dimensions and fill percentages were analyzed under a 100 kg TNT explosion at different explosive distances [23].
In this case, a water tank with a height of 1 meter, a radius of 1 meter, and 50% water fill was modeled under a 100 kg TNT explosion at a distance of 5 meters from the tank and evaluated in ABAQUS software to confirm the model's validity. The graph in Figure (2) shows the resulting hoop stress on the tank wall under blast. The hoop stress distribution along the wall at the peak blast time is examined, and pressures are applied to the water tank. In this case, the hoop stress value is determined for each node and plotted. Table (6) compares the percentage error in the study conducted by Moghadam et al. with the present study. The comparison results showed that the difference was less than 5%.

Table 6. Percentage Error of the Method by Moghadam et al. Compared to the Present Study [23]

10	9	8	7	6	5	4	3	2	1	
1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0	Depth(m)
112	184	217	288	321	379	440	496	538	549	Moghadam et al. [23]
115	192	214	295	330	389	432	510	546	564	Current study
2.7	4.3	1.4	2.4	2.8	2.6	1.8	2.8	1.5	2.7	Error (%)

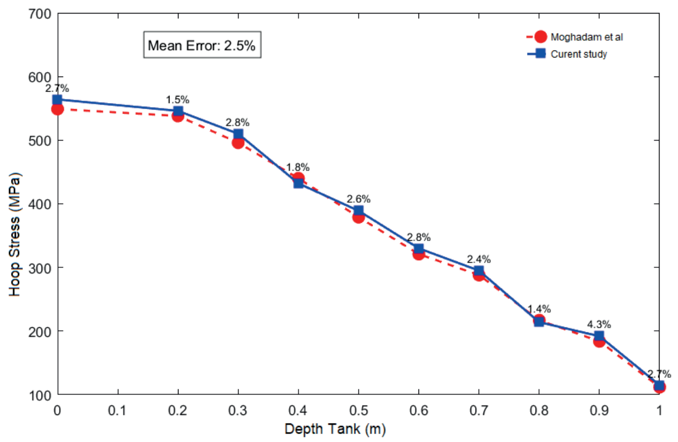

Figure 2. Comparison of hoop stress in the studied model with the research by Moghadam et al

RESULTS

Analyzed of Models

Given the variables addressed in this study, which include the water condition inside the tank (empty, half-full, and full), tank height (10 and 15 meters), explosive charge mass (500 and 1000 kg), and explosive distance (10 and 25 meters), we will examine the influence of each stated variable on the behavior of the above-ground tank, considering fluid-structure interaction effects. In this process, other variables are held constant. This procedure is repeated for each variable, and the impact of all variables on the structural response is studied and evaluated. Subsequently, the effects of explosive charge mass, explosive distance, internal water condition, and tank height on the overall response of the above-ground tank under blast loading are investigated and assessed. The studied scenarios in this research are named according to Table (7).

Table 7. Introduction and Nomenclature of the Studied Scenarios in the Present Research

Model	Tank Height (m)	Explosive Charge Mass (kg)	Water Condition in Tank	Explosive Distance (m)
T1	10	500	Empty	25
T2	10	500	Empty	10
T3	10	500	Half-Full	25
T4	10	500	Half-Full	10
T5	10	500	Full	25
T6	10	500	Full	10
T7	10	1000	Empty	25
T8	10	1000	Empty	10
T9	10	1000	Half-Full	25
T10	10	1000	Half-Full	10
T11	10	1000	Full	25
T12	10	1000	Full	10
T13	15	500	Empty	25
T14	15	500	Empty	10
T15	15	500	Half-Full	25
T16	15	500	Half-Full	10
T17	15	500	Full	25
T18	15	500	Full	10
T19	15	1000	Empty	25
T20	15	1000	Empty	10
T21 (RM)	15	1000	Half-Full	25
T22	15	1000	Half-Full	10
T23	15	1000	Full	25
T24	15	1000	Full	10

ABAQUS Software Outputs

After simulating all 24 models in ABAQUS software, contour outputs of hoop stress and displacement are obtained.

Table 8. Maximum Hoop Stress and Displacement Values for All 24 Models

Maximum Displacement (cm)	Maximum Hoop Stress (MPa)	Model
1.12	17.4	T1
2.41	43.4	T2
1.40	24.8	T3
3.40	61.9	T4
1.62	29.7	T5
4.11	74.3	T6
1.20	21.7	T7

3.00	54.2	T8
1.70	30.9	T9
4.30	77.4	T10
2.00	37.1	T11
5.10	92.8	T12
1.10	20.4	T13
2.80	51.0	T14
1.64	29.1	T15
4.15	72.8	T16
1.90	34.9	T17
4.80	87.4	T18
1.40	25.5	T19
3.55	63.7	T20
2.09	36.4	T21 (RM)
5.00	91.0	T22
2.42	43.7	T23
6.12	109.2	T24

Optimal Design of the Cylindrical Reinforced Concrete Tank

The Particle Swarm Optimization (PSO) algorithm is a population-based optimization technique inspired by the social behavior of bird flocking or fish schooling. Each "particle" in the search space represents a potential solution. The main parameters of this algorithm are as follows:

- Population: A set of particles (n-particles).
- Position: The location of a particle in the search space (positions).
- Velocity: The direction and magnitude of a particle's movement (velocities).
- Personal Best: The best position experienced by each particle so far (pBest).
- Global Best: The best position found within the entire swarm (gBest).

The velocity and position of each particle are updated using Equations (4) and (5).

$$v_i(t+1) = w \times v_i(t) + c_1 \times r_1 \times (pBest_i - x_i(t)) + c_2 \times r_2 \times (gBest - x_i(t)) \quad (4)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (5)$$

Where:

- $v_i(t)$ is the velocity of particle i at iteration t,
- $x_i(t)$ is the position of particle i at iteration t,
- w is the inertia weight,
- c_1 and c_2 are the cognitive and social acceleration coefficients, respectively,
- r_1 and r_2 are random numbers uniformly distributed between 0 and 1,
- $pB\ est$ is the personal best position of particle i, and
- $gBest$ is the global best position.

In this section, using the results from Table 5, a cylindrical reinforced concrete tank was designed using the PSO algorithm. The algorithm parameters were set as presented in Table 9.

Table 9. Initial parameters of the PSO algorithm

Maximum Number of Iterations	Cognitive Coefficient	Social Coefficient	Inertia Weight (w)	Number of Particles
100	1.5	1.5	0.7	50

It should be noted that the two design constraints were set as the maximum allowable hoop stress (30MPa) and maximum displacement (20mm). The optimal tank was designed for C30 concrete and steel with a yield strength of 400MPa. The tank height and diameter were 15 m and 33.85 m, respectively. The explosive mass and explosive distance were considered as 5000 kg and 50 m, respectively. In this optimal design, the objective function was to minimize the tank weight while simultaneously satisfying the maximum stress and displacement constraints. According to the executed code provided in Appendix (C), the minimum weight of the cylindrical reinforced concrete tank using the PSO algorithm is 23933kN, which, as shown in Figure (3), is achieved after approximately 25 iterations.

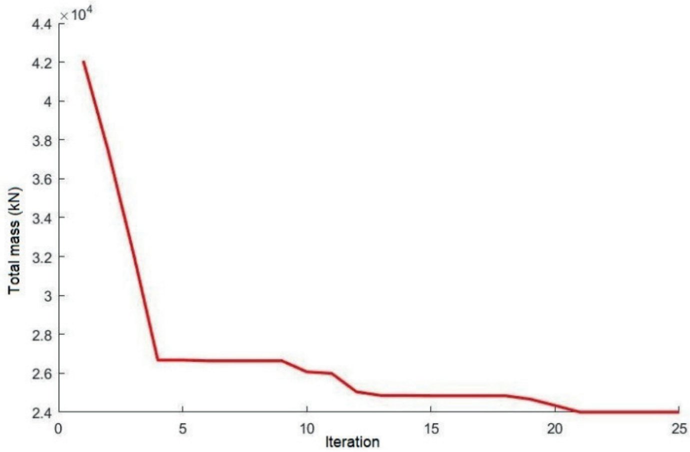

Figure 3. Optimized weight of the cylindrical reinforced concrete tank versus PSO algorithm iterations

Table 10 presents the geometric specifications of the weight-optimized cylindrical reinforced concrete tank.

Table 10. Geometric specifications of the optimal tank using the PSO algorithm

Parameter	Value
Total tank height	15m
Outer diameter of the cylindrical tank base	33.85m
Concrete cover for floor and wall	50mm
Tank wall thickness	440mm
Vertical reinforcement	Two layers of Φ25@150mm
Horizontal reinforcement (hoops)	Two layers of Φ32@150mm
Maximum hoop stress	26.76MPa
Maximum displacement	2.01cm

Determination of Fitted Curves for Problem Parameters

A fitted line (trend line) is a straight line that represents the best linear relationship between two variables. This line is drawn such that the overall distance of all data points from the line is minimized, while also passing through the majority of the data. In this section, the fitted line (regression) between various parameters and the hoop stress is calculated. The goal is to find the equation of a straight line $y = ax + b$ that best fits the data. To compute the slope and intercept of this line using the least squares method, Equations (6) and (7) are used.

$$a = \frac{\sum_{i=1}^{1000}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{1000}(x_i - \bar{x})^2} \tag{6}$$

$$b = \bar{y} - a\bar{x} \tag{7}$$

Where $\bar{x}$ and $\bar{y}$ are the means of the n data points on the horizontal and vertical axes, respectively. According to Figure (4), an inverse and approximately linear relationship is observed between mesh size and hoop stress. As the mesh size decreases from 0.3m to 0.03m, the hoop stress increases from 5MPa to 55MPa. Finer meshing is capable of estimating the complex stress field resulting from the interaction of the blast wave and sloshing phenomena with higher accuracy. This relationship also indicates a strong dependence of the finite element analysis results on the mesh size.

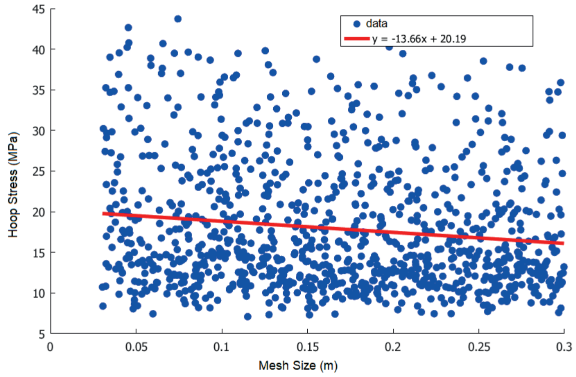

Figure 4. Correlation between hoop stress and mesh size

According to Figure (5), a parabolic relationship is observed with maximum stress occurring at a fluid height of 4-6 meters. At low fluid levels, the impulsive effect of the blast wave dominates. At moderate fluid heights, the phenomena of fluid-structure resonance and sloshing occur, while at high fluid levels, the damping effect of the fluid and hydrostatic pressure become significant.

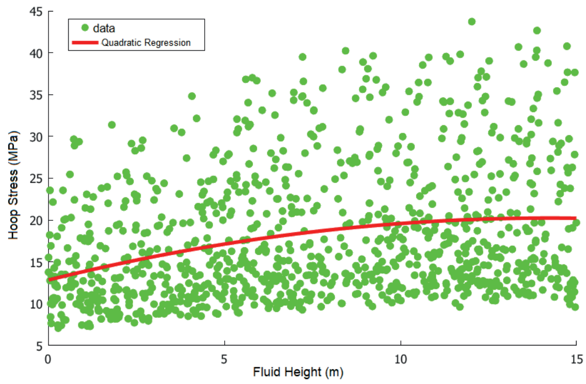

Figure 5. Correlation between hoop stress and fluid height

According to Figure (6), an increase in tank height has a negligible impact on the increase in hoop stress, with only a mild slope of growth. In contrast, as shown in Figure (7), increasing the explosive distance of the explosive from the tank causes a reduction in the tank's hoop stresses. Based on the present study, this parameter (explosive distance) is the most influential on the magnitude of hoop stress.

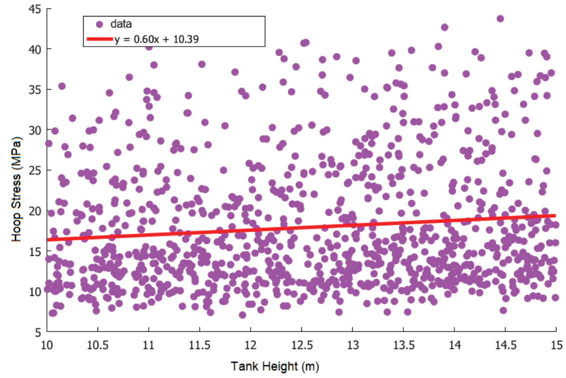

Figure 6. Correlation between hoop stress and tank height

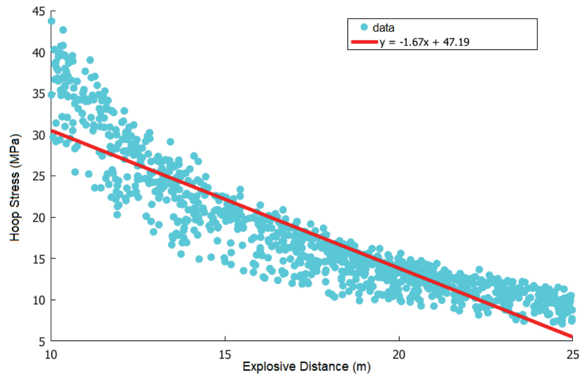

Figure 7. Correlation between hoop stress and explosive distance

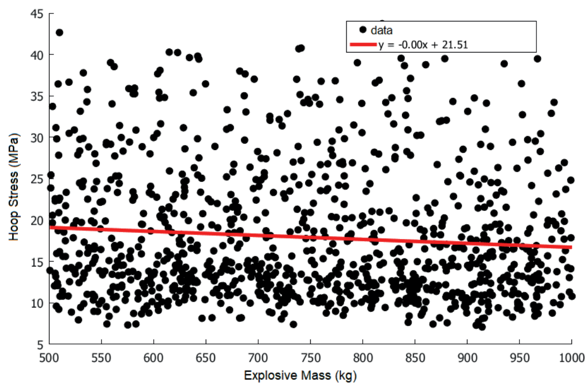

Figure 8. Correlation between hoop stress and explosive mass

As evident from Figure 8, increasing or decreasing the explosive mass within the variable distance range of 10 to 25 meters has an insignificant effect on the magnitude of hoop stress. This demonstrates the negligible influence of charge mass on hoop stress at larger standoff distances from the tank.

DISCUSSION AND CONCLUSION

In this research, the dynamic responses of cylindrical reinforced concrete water storage tanks under specified blast loading were investigated. The results indicate that parameters such as the water fill level, tank height-to-radius ratio, and distance from the blast center significantly influence the dynamic response of the tank structure. Specifically, the horizontal impulse increases with a decrease in water fill percentage and an increase in tank height. Furthermore, hoop stresses increase with a higher water fill level and a decrease in the standoff distance of the explosive. The most significant findings of this study are as follows:

- The optimal design of a cylindrical reinforced concrete tank using the Particle Swarm Optimization (PSO) algorithm for a specified fluid volume resulted in a reduction of the tank weight by approximately 4% after 25 iterations.
- A decrease in mesh size led to an increase in hoop stress, which is primarily attributed to stress concentration in the underlying elements.
- As the fluid height inside the tank increases, hoop stresses exhibit a parabolic pattern of increase.
- Increasing the tank height within the range of 10 to 15 meters does not significantly alter the hoop stresses.

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