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NUMERICAL MODELING AND SIMULATION-BASED ASSESSMENT OF UNDERWATER EXPLOSION EFFECTS NEAR AN OFFSHORE OIL AND GAS EXTRACTION PLATFORM

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Abstract: *In the context of increasing security threats in the Black Sea region due to naval mine deployment, this study investigates the potential impact of underwater explosions on offshore oil and gas platforms. Using numerical simulations in ANSYS, the research analyzes the structural response of an offshore platform subjected to a detonation from a drifting YaM-type naval mine. The study begins with a two-dimensional simulation to validate peak pressure values and shock wave propagation, followed by a three-dimensional model of a four-legged platform under explosive loading conditions. Results show a deformation depth of approximately 26 cm in the impacted leg and a longitudinal displacement of 3.63 mm. Passive protection solutions, such as deploying nets around offshore platforms, are discussed as potential methods to mitigate shock wave effects by increasing the standoff distance. The findings highlight the vulnerability of critical maritime infrastructure and emphasize the importance of developing effective risk mitigation strategies to counteract threats posed by drifting naval mines. This research contributes to improving the resilience of offshore structures and lays the groundwork for future experimental studies on underwater blast effects and protective system design.*

Keywords: offshore, naval mines, underwater explosion, simulation

1. Introduction

In the current geopolitical climate, the war of aggression launched by the Russian Federation against Ukraine in 2022 has generated multiple security risks in the Black Sea region. Among the multifaceted risks, the deployment of naval mines by both Russian and Ukrainian forces poses a particularly acute threat with significant implications for regional security, international trade, and critical maritime infrastructure[1].

In an effort to protect its coastline and critical maritime infrastructure, Ukraine has resorted to the use of naval mines, aiming to hinder Russian naval activity and reinforce control over strategic sea areas. These naval mines, initially anchored, have become increasingly hazardous due to detachment and uncontrolled drift caused by hydrodynamic forces. As a result, the territorial waters of neighbouring states such as Romania, Turkey, and Bulgaria have been exposed to potential mine-related incidents [2][3].

The unpredictable drift and uncertain location of these mines significantly increase navigational risk, contributing to economic instability in the region, as the Black Sea is a crucial transit point for

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global trade. For instance, the Estonian-owned M/V Helt sank in the Black Sea after striking a mine approximately 40 kilometres south of Odessa [4].

Understanding the nature of maritime threats is a critical first step in assessing security risks in the Black Sea region. The naval mines deployed by the belligerents range from rudimentary contact mines to advanced, sensor-equipped systems. At the most basic levels, contact mines, typically moored below the waterline, contain high-explosive charges and are designed to detonate upon direct physical contact. These are frequently deployed near harbours or strategic straits to block access.

In contrast, more advanced mines, such as magnetic, acoustic, or pressure-activated types, are capable of identifying and responding to specific vessel signatures and, in some cases, may be remotely programmed or selectively triggered, increasing their strategic utility and operational effectiveness.[5], [6] Drifting mines, in particular, represent a major navigational hazard due to their unpredictable movement and limited traceability. Examples of such mines found in the Black Sea, originating from the Ukrainian coastline, include the R-421-75, YaM (or MYaM), and YaRM contact mine types [2].

Moreover, the emergence of improvised naval mines (INMs), including repurposed civilian vessels loaded with explosives, reflects adaptive responses to resource limitations, particularly on the Ukrainian side. The strategic utility of naval mines in establishing sea-denial zones and disrupting maritime logistics underscores their continued relevance in modern conflicts, especially in semi-enclosed seas like the Black Sea, where littoral dynamics and commercial significance converge.

As drifting naval mines increasingly jeopardize both commercial and military maritime activities, it is essential to evaluate the risks associated with accidental contact, particularly those affecting critical offshore assets. Oil and gas platforms operating in the Black Sea represent high-value targets vulnerable to such threats. Therefore, this study seeks to investigate the potential impact of drifting mines on offshore extraction infrastructure through numerical simulations conducted using ANSYS software. The primary objective is to analyse the structural vulnerabilities of offshore platforms under explosive load conditions and to contribute to the development of design reinforcement and risk mitigation strategies.

One of the most commonly encountered drifting mines in the waters of the Black Sea is the YaM-type mine. According to open-source information available online, it has the following technical specifications [7]:

- total mass of the moored mine: 275 kg;
- mass of the live mine (excluding anchor): 115 kg;
- mass of the explosive charge: 40 kg;
- type of explosive: TNT (Trinitrotoluene).

Another well-known mine is the R-1 riverine mine, which is loaded with 20 kg of explosive [7].

Figure 1: YaM naval mine [2]

2. Underwater Explosion

An explosive detonated in water represent a critical hazard in maritime environments, due to the conversion of the explosive material into hot gases which reach approximately 3000°C and produce a shock pressure up to 5000 MPa [8], especially near sensitive infrastructures such as offshore oil and gas platforms. The propagation of explosive shock waves in water is significantly more intense than in air due to the higher density and low compressibility of water. In this context, the peak overpressure generated by the detonation far exceeds the hydrostatic pressure by several orders of magnitude. Due to this significant disparity, the contribution of hydrostatic pressure becomes negligible in analytical and numerical models. As a result, the term peak pressure is used exclusively to denote the maximum pressure at the shock wave front.

The pressure-time profile of an underwater shock wave, especially in an unbounded water field, is characterized by a rapidly increase to this peak pressure value. Immediately following this initial spike, the pressure decreases rapidly, following an exponential path. This occurs due to the dissipation of energy as the shock wave propagates through the water medium, where compressibility effects play a significant role. Accurately capturing this pressure-time history is crucial for understanding the dynamic loading transmitted by underwater explosions on nearby structures, which is given by the following empirical relation [8]:

$$P(t) = P_m e^{-\frac{t}{\theta}} \tag{1}$$

where P_m is the peak pressure of the shock wave, θ is the exponential decay time constant and t is time;

$$P_m = k_1 \bullet \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\alpha_1} \tag{2}$$

$$\theta = k_2 \bullet W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\alpha_2} \tag{3}$$

where W is the weight of explosives, and $k_1 = 52.16\ MPa$, $k_2 = 96.5 \bullet 10^{-6}$, $\alpha_1 = 1.13$ and $\alpha_2 = -0.22$ are constants [9].

To assess the reliability of the numerical model and to analyze the propagation characteristics of the shock wave, a 2D free-field underwater explosion scenario was numerically simulated, to facilitate the calibration of material models employed in the 3D model. In the absence of available experimental data, the numerical results were subsequently compared against established empirical equations available in the literature, to validate the model's accuracy and predictive capability.

For this purpose, the axisymmetric two-dimensional configuration shown in Figure 2 was established, where a 50 kg spherical TNT charge was positioned at the water surface.

The material models and the equations of state used are presented in Table 1.

Table 1: Materials models used in the bi-dimensional simulation [10], [11]

Parameter	**Materials**		
	TNT	**Air**	**Water**
Material model	*MAT_HIGH_EXPLOSIVE_BURN	*MAT_NULL	*MAT_NULL
Density	1,63 g/cm^3	-	1000 kg/m^3
Detonation velocity	6930 *m/s*	-	-
Chapman-Jouget pressure	21 *GPa*	-	-
Internal energy density (E0)	7 *GPa*	-	-
Initial density	-	1,293 kg/m^3	-
	-		-
Initial pressure	-	1 *Bar*	-
Ratio of specific heats	-	1,4	-
Equation of state (EOS)	JWL	LINEAR_POLYNOMIAL	GRUENEISEN
EOS parameters	ω=0,30 A=371,213 *GPa* B=3,2306 *GPa* R_1=4,15 R_2=0,95	C4=C5=0,4 [11]	C=1435 *m/s* S_1=2,56 S_1=-1,9086 S_1=0,227 γ_0=0,5

The Johnson-Cook material model parameters for the column steel those presented in [13].

In order to observe the pressure-time evolution in both media, air and water, a series of tracers was introduced in the model, as can be seen in Figure 2. The distance between two tracers is 0,5 m.

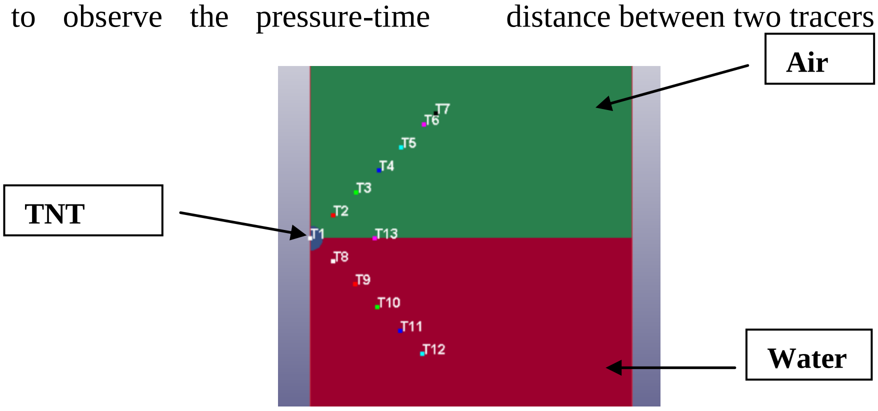

Figure 2: The setup of the gauges that were set to trace the pressure-evolution by distance travelled in water

2.1. Bi-dimensional Simulation Results Comparison

Figure 3 shows the time evolution of the pressure recorded by the virtual sensor T9, as positioned in Figure 2.

By applying equations (1) – (3) for a 50 kg explosive charge, at 0,96 and 1,46 meters from the centre of the explosive sphere, a pressure–time graph was obtained, as shown in Figure 4.

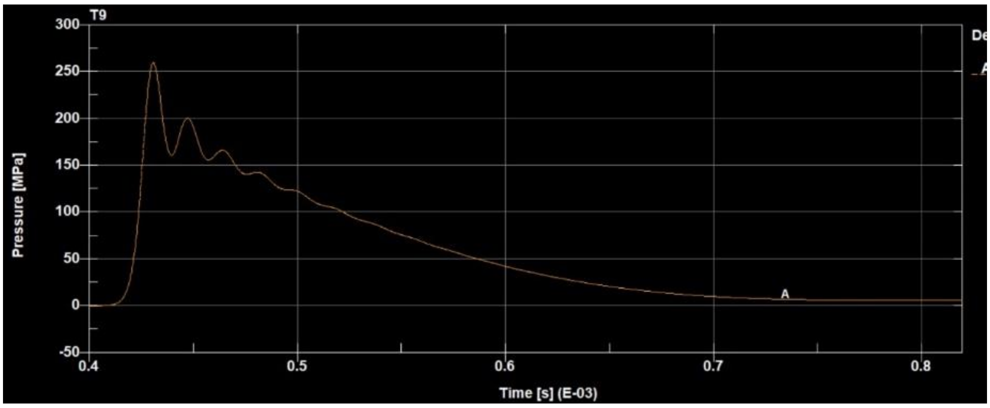

Figure 3: T9 tracer pressure vs time profile

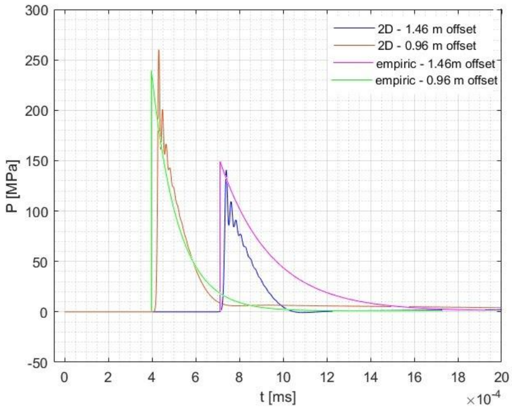

Figure 4: Comparison between bi-dimensional simulation and empirical calculations

3. Three-Dimensional Simulation

In order to evaluate the effects caused by the detonation of a drifting naval mine on an offshore oil platform, this study proposes the configuration presented in Figure 5.

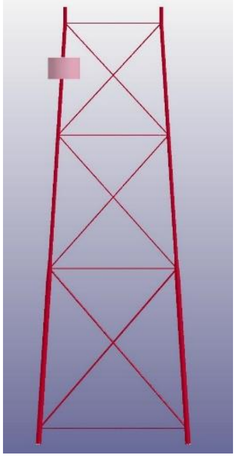

Figure 5: The proposed platform configuration for modelling and simulation

As part of a simplified working hypothesis, the offshore structure is modelled as a four-legged platform with an assumed height of 80 meters. A spherical TNT charge with a mass of 50 kg is hypothetically placed near one of the legs of the structure. The water depth is assumed to be 70 meters.
Each support column of the platform is modelled with a diameter of 70 cm and a wall thickness of 4 cm. A virtual load equivalent to a total mass of 1350 tons is uniformly distributed across the four legs to approximate the operational loading conditions.
The surrounding water column is represented as a cylindrical volume encompassing the impact zone near the explosive, with an assumed height of 1,5 meters and diameter of 6 meters.
The material models used in this simulation are consistent with those previously applied in the 2D analysis of the detonation phenomenon.

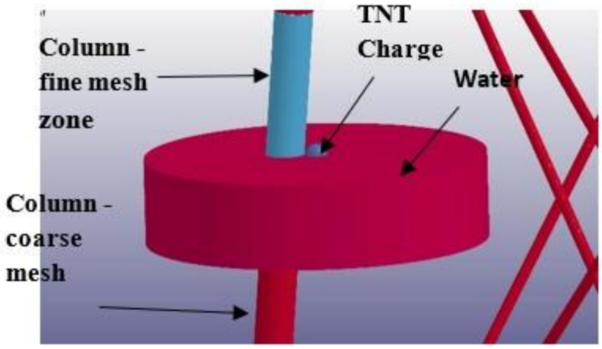

Figure 6: The three-dimensional modelling and simulation setup

Figure 7 illustrates the level of discretization of the 3D model within the ALE (Arbitrary Lagrangian-Eulerian) domain.

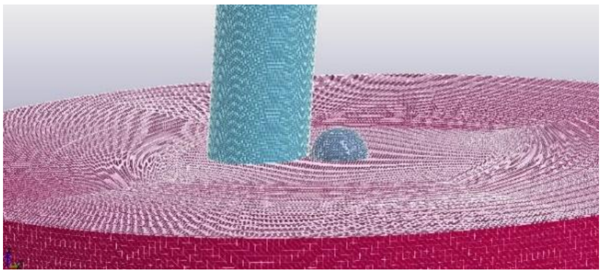
Figure 7: The discretization level of the influence zone of the simulation

4. Results and Discussions
Following the execution of the 3D model simulation, the analysis focused on the recorded data regarding the deformations experienced by the platform leg and the longitudinal strains along the leg.

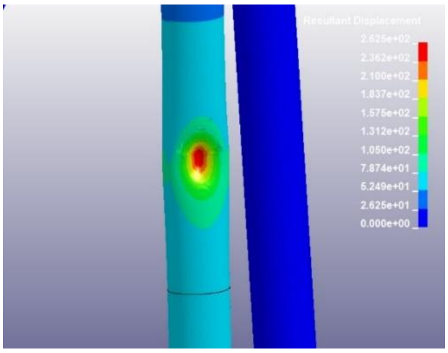
Figure 8: State of deformation of the column, at moment t=150 ms

Figure 9 highlights the deformation state of the platform leg after 150 ms of simulation time, showing a deformation depth of approximately 26 cm.

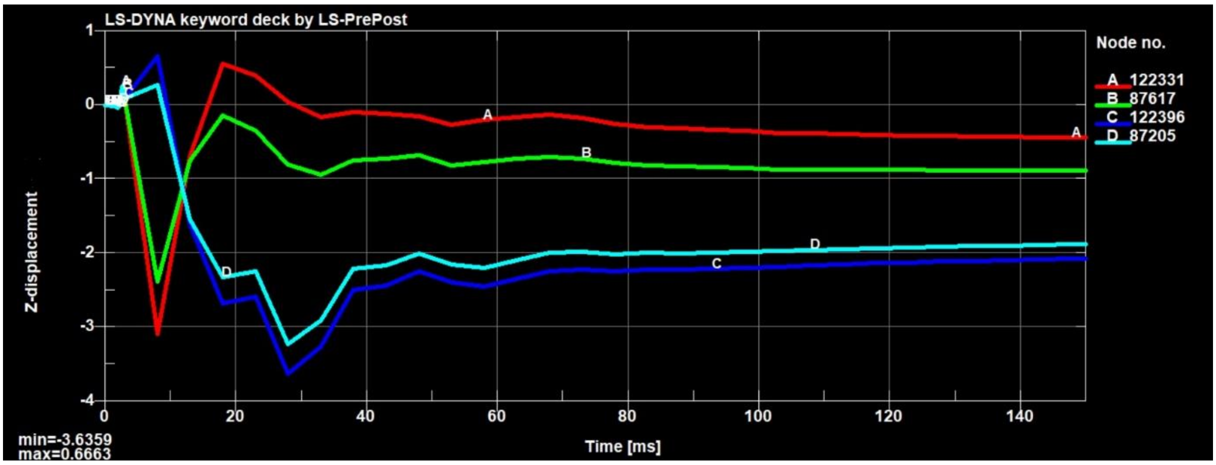

Figure 5: Z displacement for the upper surface of the column (the displacement is to be read in mm)

Regarding the longitudinal deformations of the affected platform leg, Figure 10 shows the displacement in the Z-direction of its upper surface. To enable visualization of this displacement, the nodes highlighted in Figure 11 were selected for analysis.

At *t=26 ms*, the maximum displacement of the mentioned surface was approximately 3.63 mm.

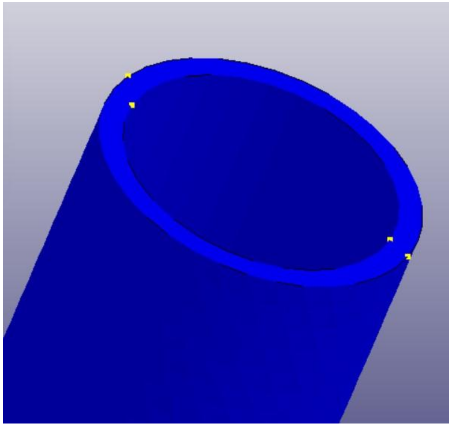
Figure 10: The nodes (yellow points) selected from the upper part of the column to measure the Z displacement

5. Conclusions

Based on the results obtained from the three-dimensional simulation, it can be observed that the effects of a naval mine explosion can cause significant damage to the structural integrity of an offshore extraction platform. It is also important to note that, for the problem under consideration, simplifying assumptions were applied to reduce computation time, considering the available processing power. The simulation was therefore stopped at 150 ms, which did not allow for the observation of longer-term shock effects. Only the longitudinal displacement of the platform leg's upper surface was highlighted for this short duration, without capturing any potential oscillatory behaviour of the platform, which could plausibly occur under such conditions.

Currently identified solutions for neutralizing naval or riverine mines consist of unmanned surface or underwater vehicles, equipped with various mine-detection subsystems, such as sonar systems [14].

To prevent such events, a passive protection solution, such as the deployment of nets around offshore platforms, could serve to stop naval mines at a safe distance from the platform legs. This would allow, in the event of mine detonation, for the attenuation of shock wave effects, as the overpressure in the shock front decreases with distance, a phenomenon discussed in Section 2.1.

Given the limited number of available protective solutions for offshore platforms, new research directions can be proposed to experimentally investigate the effects of explosive detonations on underwater structures. The objective would be to determine the requirements that a potential passive protection system must meet, as well as to assess the technical feasibility of such solutions.

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