Journal of Marine Science and Application (2022) 21: 168-176
https://doi.org/10.1007/s11804-022-00306-6

RESEARCH ARTICLE

Nonlinear Dynamic Response of a Fixed Offshore Platform Subjected to Underwater Explosion at Different Distances

Seyed Shahab Emamzadeh[1]

Received: 12-Apr-2022 / Accepted: 01-Oct-2022

Abstract

In this paper, the dynamic response of a fixed offshore platform subjected to the underwater explosion (UNDEX) and probable events following it have been investigated. The pressure load due to UNDEX in a specified depth has been applied with a model that considers the effect of blast bubble fluctuations into account. The effect of water on the natural frequency and Fluid-Structure interaction has been modeled as equivalent added mass formulation. The effect of explosion distance on platform response is studied. In this regard, three cases of near, medium, and far-distance explosions are considered. For a case study, a real fixed offshore jacket platform, installed in the Persian Gulf, has been examined. Only the UNDEX pressure load is considered and other dynamic loads such as surface water waves and winds have been neglected. Dead loads, live loads and hydrostatic pressure has been considered in the static case based on the design codes. The results indicated that in near-distance explosions, the UNDEX pressure load can locally damage parts of the platform that are located at the same level as that of explosive material and it can destabilize the platform. In the medium to far distance explosion, a very large base shear was applied to the platform because more elements were exposed to the UNDEX load compared to the near-distance explosion. Therefore, precautionary measures against UNDEX such as risk assessment according to design codes are necessary. As a result of this, member strengthening against explosion may be required.

Keywords Dynamic response; Water pressure; Underwater explosion; Added mass; Offshore platforms

1 Introduction

Offshore platforms are usually made to extract oil and gas from the seabed. An important factor in the design and analysis of offshore platforms is the accurate prediction of exerted loads. In operation time there is a possibility for accidental loads. Collision and explosion are among possible accidental loads. Numerous studies have focused on the accidental loading of marine platforms and design codes have incorporated the findings of those studies. For example, in the American Petroleum Institute (API, 2014) there is a chapter about accidental loading such as blast and fire, in which, while defining various levels of risk, an algorithm is presented that can be used for the probabilistic risk assessment of a platform. In this code, it is stated that the accidental loads could induce minor to overall damage to a platform, death of the crew, and also environmental pollution. Therefore, to minimize these negative effects, the study of accidental loads in the design stage is necessary. In the Norwegian Det Norske Veritas (DNV, 2011) standard, there is a section named accidental loads and the blast load is a part of it. In this standard, accidental loads should be determined based on the experience and assessment of the designer.

One of the loading scenarios considered by design standards is the shock wave pressure due to the underwater explosion. Efforts for simulation of the blast wave propaga-

Article Highlights

- The obtained outcomes may help to understand the structural response of fixed offshore jacket structures against underwater explosions;
- The effect of underwater explosion source distance on the structural response of fixed offshore are studied;
- The bubble dynamics of an underwater explosion are considered which controls structural loading, stresses and damage.

✉ Seyed Shahab Emamzadeh
shemamzadeh@khu.ac.ir

[1] Faculty of Civil Engineering Group, Engineering Department, Kharazimi University, Tehran, Iran

tion go back to the research done during World War II. Cole 1948 discussed the analytic and laboratory simulation methods used for studying underwater blast wave propagation at that time. A summary of more recent methods is given by Mair (1999a). Similar investigations were made on floating bodies like ships and submarines for military and defense purposes. Up to now, various empirical relationships have been proposed for underwater blast loading. In some of them, the effects of blast bubble fluctuation and its run-up are considered. The Geers and Hunter (2002) model is among those models, which is applied in this article.

The numerical simulation of underwater blast wave propagation was first investigated in the 1970s using the finite difference method and then the finite volume method. Based on those investigations, computer programs were prepared. Mair (1999b) presented a summary of those programs. In recent years many researchers have focused on the development of numerical methods for solving the governing equations of shock wave propagation. For more recent research in this regard, the work of Sprague and Geers (2006) can be mentioned, where the shock wave propagation due to underwater blast has been simulated by a spectral element method. In addition, by defining a criterion for the pressure, the cavitation induced by blast wave-structure interaction was investigated. In similar works, Emamzadeh et al. (2015) proposed an adaptive finite element for wave propagation due to UNDEX. For the water-structure interaction and problems related to the interface boundary one could refer to the recent works of Ross et al. (2008, 2009) in which by defining the local Lagrangian coefficients, the interaction forces between meshes of non-conforming water and structure are calculated and compared with other methods. There are numerous studies on the effect of blast loading on civil engineering structures. Comprehensive experimental and numerical investigations have been conducted related to the blast effects on buildings (Lu and Wang, 2006; Tian and Li, 2008; Jayasooriya et al., 2011; Parisi and Augenti, 2012), marine structures (Zhang et al., 2011; Jin and Ding, 2011), underground structures (Lu et al., 2005; Wang et al., 2005; Ma et al., 2011; Li et al., 2013), bridge structures (Tang and Hao, 2010; Hao and Tang, 2010; Son and Lee, 2011; Anwarul Islam and Yazdani, 2008), dams (Zhang, 2014), plate and shell structures (Rajendran and Lee, 2009; Wang et al., 2013; Zakrisson et al., 2011; Spranghers et al., 2013; Biglarkhani and Sadeghi, 2017) and so on. However, corresponding studies on the effect of blast loading on jacket platforms subjected to UNDEX are limited.

Despite the strategic and economic importance of the offshore platforms, there is little understanding of the response of these structures to the underwater explosion. The main objective of the present research is the response analysis of a jacket offshore platform to UNDEX loading and the possible events following it. The UNDEX could occur on the platform or away from it.

2 Underwater explosion loading on offshore platform

In Figure 1 a typical jacket platform is shown. Shock waves that encounter the platforms after a UNDEX are illustrated in Figure 2. As is shown the explosive material is located at a certain distance from the platform. The resultant blast wave propagates through the water and reaches the platform legs. In addition, several minor peaks due to bubble oscillations are illustrated in the shock profile.

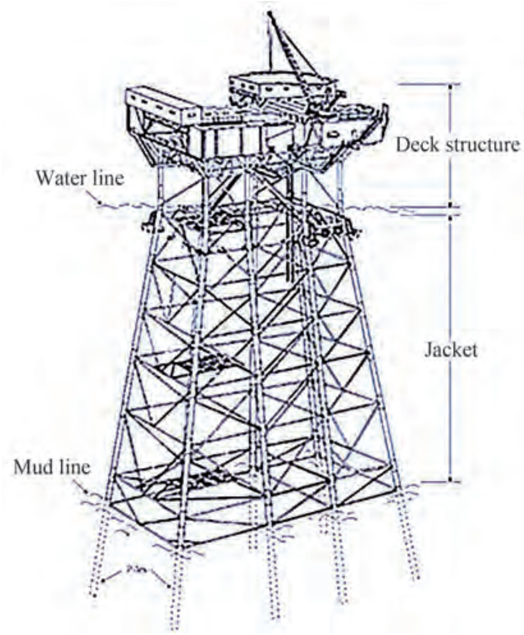

Figure 1 Major components of a jacket platform (Continental Shelf Associates, Inc., 2004)

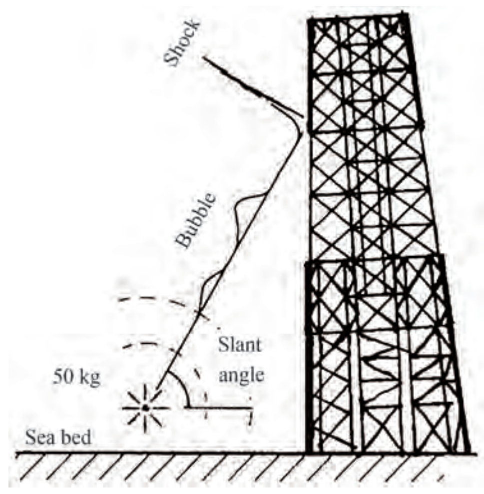

Figure 2 Shock wave encounter with a fixed jacket platform (Bangash, 1993)

This paper presents a numerical method in the time domain for the response analysis of an offshore platform subject to UNDEX loading. The proposed method is developed to simulate the behavior of fixed jacket platforms with truss elements. In section 2, the loading due to underwater explosion is formulated by introducing a pressure function based on Geers-Hunter (2002) model. Numerical methods used for dynamic analysis of the platform are presented in section 3. In section 4 the UNDEX response of a real jacket platform in the Persian Gulf is investigated. The results of this analysis are discussed in section 5, where weak points of the platform structure under UNDEX loading are indicated. Finally, the concluding remarks are given in section 6.

The equilibrium equation for small motions of an acoustic fluid with velocity-dependent losses is taken to be as (Emamzadeh et al., 2015):

$$\nabla p + \gamma \dot{u}^f + \rho_f \ddot{u}^f = 0 \tag{1}$$

where p is hydrodynamic pressure in excess of hydrostatic pressure. $\dot{u}^f$, $\ddot{u}^f$ are velocity and acceleration vectors of flow fluid, respectively. ρ_f is fluid density and γ is the "volumetric drag" (force per unit volume for unit velocity).

Fluid behavior is assumed to be inviscid, linear, and compressible, so

$$p = -K_f(\nabla \cdot u^f) \tag{2}$$

where K_f and u^f are the bulk modulus and displacement vector of fluid particles, respectively.

2.1 Bubble fluctuation effects

The failure mechanisms of structures might not be accurate if only shock wave is considered (Wang et al., 2016) demonstrated that the UNDEX bubble collapse jet local load plays a more significant role than the UNDEX shock wave load, especially in a near-field underwater explosion.

In practical applications, the structural response, deformation, and motion can significantly affect the bubble dynamics which controls structural loading, stresses, erosion, and damage. Significant effects due to the structural response on the bubble dynamics are observed including modification of the bubble period, re-entrant jet formation, and pressure generated on the solid body. These results indicate that structural characteristics can significantly affect erosion and damage to a structure by nearby cavitation or explosion bubbles (Kalumuck et al., 1995).

Through the comparison of bubble dynamics near a movable and a fixed plate, the FSI effect is found to induce a significant increase in the jet impact velocity and the corresponding impact pressure (Hu et al., 2021).

Numerous relationships have been proposed in the literature to model the loading due to underwater explosion. In some of these relations, the fluctuations of the blast bubble and its run-up towards the water surface are considered. One of those relationships is the Geers-Hunter (2002) model which is used here for the determination of far-distance blast wave pressure.

In this model, it is assumed that as a consequence of an underwater blast, a pressure bubble is formed whose radius and pressure are functions of the explosive material depth. Figure 3 depicts the fluctuation of the blast bubble and its motion towards the water surface in this model.

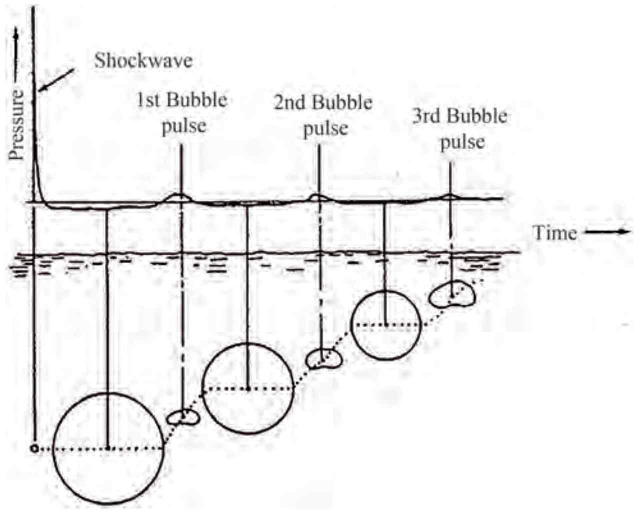

Figure 3 Pressure history and motion of the blast-induced bubble (Geers-Hunter, 2002)

2.2 Underwater explosion Pressure

According to Geers-Hunter (2002) model, the pressure due to underwater blast, P, at a distance r from the explosion center at time t, is derived from the following equation:

$$P(r,t) = P_c\left[\frac{a_c}{r}\right]^{1+A} f(\tau) \tag{3}$$

$$\tau = \left[\frac{a_c}{r}\right]^{B} (v_c t/a_c) \tag{4}$$

in which r is the distance from the center of the explosive charge with a radius a_c, and P_c, v_c, A and B are constants associated with the charge material. Some recommended values for these constants appear in Table 1.

Table 1 Coefficients of the explosive materials (Geers-Hunter, 2002)

Material	P_c (GPa)	v_c (km/s)	A	B
TNT (1.52g/cc)	1.42	0.992	0.13	0.18

The function $f(\tau)$ is given by the following expression:

$$f(\tau) = e^{-\tau} \quad \tau \leqslant 1 \tag{5}$$

$$f(\tau) = 0.825e^{-1.338\tau} + 0.174\,9e^{-0.180\,5\tau} \quad \tau \leqslant 7 \tag{6}$$

In Eq. (3) which $\tau \leqslant 1$, corresponds to the first part of the loading where the blast bubble is formed, while in Eq. (4) which $\tau \leqslant 7$, is related to the subsequent part of the loading where the pressure reaches 5% of its maximum value and the blast bubble fluctuations occur around the balance radius.

3 Explosion response analysis

The main role of the bracing system is the transmission of the lateral loads to the foundation. The vertical legs of the platform are connected by bracings and they together form a rigid framework. There are three types of bracings: (1) diagonal bracings in the vertical planes, (2) horizontal bracings, and (3) diagonal bracings in the horizontal planes. The explosion response analysis aims to check the jacket and deck structural sufficiency against underwater blast loading according to the requirements of the API code. In an approximate simulation, the platform legs, risers, and deck are usually modeled as a beam, beam-column and rigid elements, respectively. The beam elements are used when one dimension of the structure is significantly larger than the other two dimensions and flexural stresses are the most important. The riser behavior, especially in deep water, is close to the cable behavior and its bending stiffness could be neglected but in shallow water behave as a beam-column element. The deck is also considered to be rigid and is defined by six degrees of freedom concerning a reference point. In this research to take the effect of water-structure interaction due to underwater blast, an equivalent approximate added mass model is implemented. In this model, the effects of the dynamic pressure of water will be considered as an added inertia represented by an equivalent added mass. The dynamic equation of motion after taking the contribution of various members is in the following form:

$$\boldsymbol{M}\ddot{\boldsymbol{U}} + \boldsymbol{C}\dot{\boldsymbol{U}} + \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F}(t) \tag{7}$$

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K}$$

In Eq. (5), $\boldsymbol{U}$ is the nodal displacements vector, $\boldsymbol{M}$ is the summation of mass and added mass matrices of the platform, $\boldsymbol{C}$ is the damping matrix with α , β coefficients, $\boldsymbol{K}$ is the nonlinear stiffness matrix of the platform and $\boldsymbol{F}(t)$ is the equivalent load vector due to the blast. The incremental explicit integration method is implemented for solving the dynamic equations. The nonlinearity of the stiffness matrix is due to large deformations and plastic strains in the structural members under very large stresses induced by the blast. In deriving these equations, it is assumed that the platform members undergo an elastic-plastic large deformation. For the sake of simplicity, the nonlinearity of the members is represented with an elastoplastic model. The platform legs connection to piles cap is assumed rigid. The piles are fixed at some distance below the sea bed. The lateral movement of piles is not considered for simplicity. The added mass per unit length, m, for a cylindrical submerged member is (Hicks, 1972):

$$m = \rho_f \pi R^2 \sin^2\theta \tag{8}$$

where ρ_f is the mass density of the displaced fluid, $\boldsymbol{R}$ is the radius of the member and θ is the angle of the cylinder axis with respect to the direction of fluid motion.

4 Numerical model

To demonstrate the procedure of blast response analysis, a four-legged oil well platform with six conductors and a single heavy rigid deck in a water depth of 75 m in the Persian Gulf is considered as shown in Figure 4. The three-story platform topside includes a top deck, mezz deck, and cellar deck is modeled with a single rigid shell diaphragm for simplicity. Table 2, specifies the UNDEX charge properties used for analysis. The dimensions of the deck are 40 m × 32 m and the jacket legs meet the deck at the corners of a rectangle of size 30 m × 22.5 m, and the slope of the jacket legs is 1 : 10. In Table 3 material properties of the platform are described. The platform has braced laterally on each side panel by two diagonal steel wires. Depending on the location, the diameter of platform legs is variable from 1 to 2 meters with thicknesses of 2 cm as shown in Table 5. The legs are hinged at the top deck and seabed.

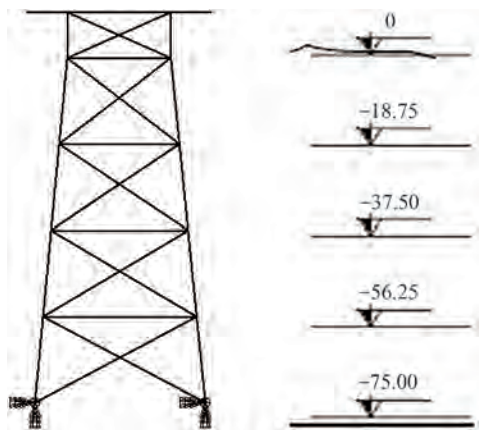

Figure 4 The topside and reference levels for investigation of the dynamic response of the platform

The explosive material is assumed to have a mass of 50 and 100 kg at a distance of 10, 30, and 60 m from the platform and at a depth of 37.5 m from the water surface. The platform behavior is investigated with respect to the blast wave. As mentioned previously, the effect of water inertia

Table 2 UNDEX charge properties

Properties	Value
Initial depth of UNDEX charge (m)	37.5
Charge weight (kg)	50 100
Nearest charge distance from the jacket (m)	10-30-60

Table 3 Material properties of the platform

Properties	Value
Mass density (kg/m^3)	7 800
Elastic Modulus (GPa)	210
Yield stress (MPa)	240
Ultimate stress (MPa)	370
Poisson's ratio	0.3
Strain rate model	Jonson cook
Failure strain (%)	20
Damping α	1.68
Damping β	0.002 56

Table 4 Geometry and Section properties of jacket members

Property	Value
Water depth (m)	75
Jacket height (m)	85
Jacket dimension at deck level (m)	30 × 22.5
Deck dimension (m)	32 × 40
Total no. of jacket legs	4
The thickness of all pipes (cm)	2
Outer Diameter of pipe sections (m)	
Legs (+0 ~ −18.75)	1
Legs (−18.75 ~ −37.5)	1.25
Legs (−37.5 ~ −56.25)	1.5
Legs (−56.25 ~ −75)	2
Horizontal brace (+0)	0.6
Horizontal brace (−18.75)	0.6
Horizontal brace (−37.5)	0.5
Horizontal brace (−56.25)	0.5
Diagonal brace (+0 ~ −18.75)	0.4
Diagonal brace (−18.75 ~ −37.5)	0.4
Diagonal brace (−37.5 ~ −56.25)	0.5
Diagonal brace (−56.25 ~ −75)	0.5

Table 5 parameters of ductile damage model

Fracture strain	Stress triaxiality	Strain rate
0.3	0.33	0.1

in the vicinity of the legs is considered by an equivalent added mass. The deck is assumed to be rigid. The dead and live loadings are applied according to the API code (2014). The wave and wind loads are neglected compared to the blast load.

The platform truss members are made of steel with elasto-plastic behavior and yield stress of 240 MPa with Ductile Damage model as presented in Table 5.

In this model, a total number of 1 159 nodes and 1 176 three-dimensional B31 beam elements, as described in ABAQUS documentation, have been used for the discretization of the jacket truss. The B31 element is a 2-node beam element with linear interpolation functions and a single integration point per element in three-dimensional space which allows for the deformation of transverse shear.

The beam elements are assumed to have a pipe cross-section. The basic assumption for the beam elements is that the cross-sections do not necessarily remain normal to the beam axis after deformation. The axial, flexural, and torsional deformations are allowed for beam elements. To apply the utilized beam theory, the ratio of the beam cross-sectional dimensions to the beam length should be less than 0.1. This criterion is usually satisfied by actual jacket-type offshore platforms.

In addition, thin-walled R3D4 shell elements, as described in Abaqus documentation (2019), are used for the deck. The R3D4 element is a three-dimensional, 4-node, rigid element. Rigid elements are modeled in the same way as the other standard elements. Rigid elements must be associated with a rigid body reference node. They can be used to discretize the surfaces of rigid bodies in contact problems. The location of explosive material is considered at mid-depth where there is the maximum distance from both the free surface and sea bed so that the effect of those surfaces can be neglected. For the sake of simplicity, the entire platform deck topside, which is usually made of multiple stories, is modeled as a rigid plate with a concentrated mass of 1 000 tons. The explicit numerical method is used for dynamic analysis. This method converges and is conditionally stable in the nonlinear analyses. In such an analysis, the convergence rate is influenced by factors such as time step and element dimensions used in the model. The overall time of blast response modeling was 0.50 seconds. The time steps used for the convergence of the model are given automatically in each step.

4.1 Modal analysis

One way to demonstrate that the model was giving sensible results is the modal analysis and finding the natural frequencies of the structure. For this purpose, the three initial modes of the jacket platform are obtained. The average period of these modes is 3.4 seconds which is typical for a Jacket platform. The mode shapes are shown in Table 6.

Table 6 Comparison of the effect of fluid loading on the first 3 modes of the platform

Mode	Excluding externalfluid (Hz)	Including externalfluid (Hz)
1	3.64	3.44
2	4.05	3.45
3	4.57	5.36

4.2 Underwater explosion analysis

To access the influence of the distance of explosive materials on the response of the steel jacket platform, three numerical models with 100 kg TNT charges and standoff distances of 10 m, 30 m, and 60 m, as shown in Figure 5, have been considered. The detonation depth is assumed to be 37.5 m. The major deformations are observed for a near, intermediate, and far distance of the explosive material from the platform. These distances are categorized based on the Unified Facilities Criteria (UFC) (2008), according to Table 7.

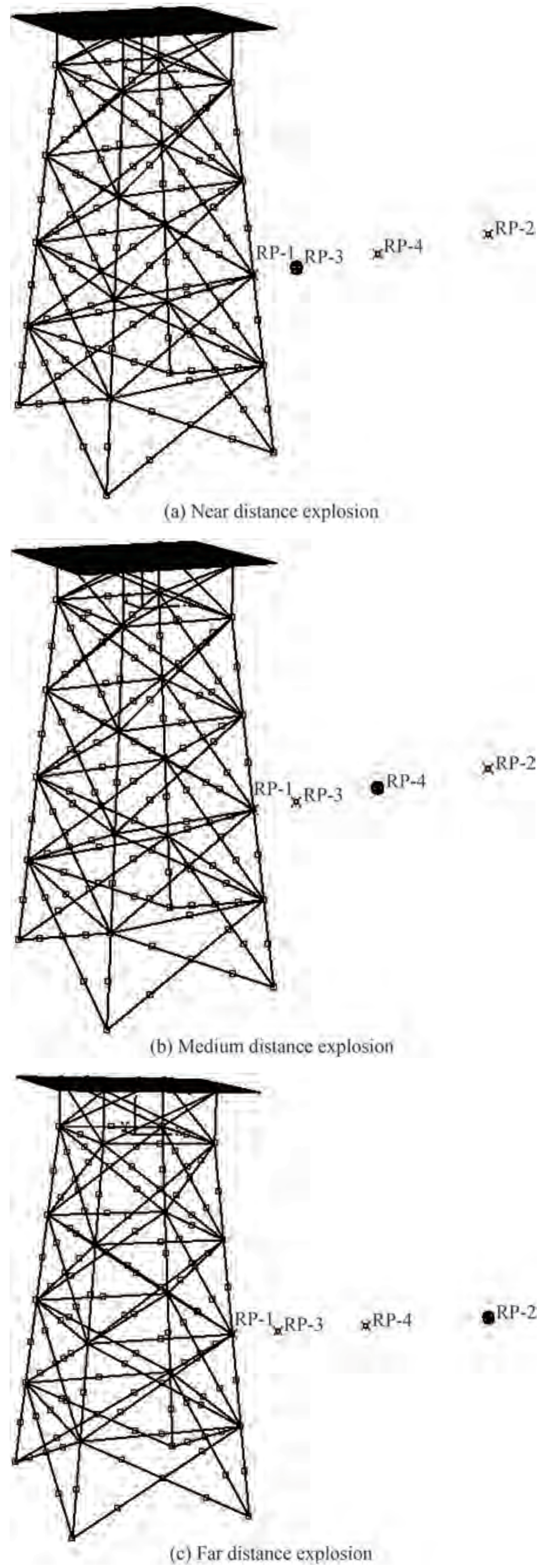

Figure 5 Range of explosive materials locations

5 Discussions and results

To investigate the platform stability, the dynamic response including the displacement and base shear is examined. Also, the deformation of the platform at different time frames after the blast is studied. The data presented in this section can be summarized in Table 8.

According to Figure 6, the base shear time history for the near explosion of 50 kg TNT has two peaks. The first peak can be due to the initial effect of the explosion wave at the standoff point, i.e., the nearest point from the explosion source to the structure. The second peak can be due to the effect of the explosion wave on the whole jacket structure.

The maximum base shear in this case reaches up to about 170 t. The medium explosion of 50 kg TNT has three peaks. This case is different from the near case. Because of the bubble pulse effect in the medium distance, an additional peak appears in the base shear time history.

The maximum base shear, in this case, amounts to about 140 tons. Finally, the base shear in the far-field reaches up to about 1 300 tons, because in this case the whole platform is affected by blast waves due to an underwater explosion.

As shown in Figure 8 in the medium-distance explosion the same quantity has three peaks. The maximum base shear in this case reaches up to about 210 t. Finally, base shear in far distances amounts to about 2 900 t. The high value of base shear can be due to the larger wavefront affected zone. Evidently, in far-distance explosions, larger parts of the jacket structure are affected compared to the near-field explosions.

Table 7 Range of explosive materials weight and distance

Project code	Distance of TNT (m)	Location relative to the jacket	Weight of TNT (kg)
N-100	10	Near	100
M-100	30	Medium	
F-100	60	Far	

Table 8 Summarized data for scenarios

		Near (N-100)	Medium (M-100)	Far (F-100)
Maximum base shear (t)		897	483	324
Maximum displacement (mm)	z0	5.2	2.7	1.9
	z1875	4.2	2.4	1.8
	z3750	4.9	2.1	1.6
	z5625	2.3	1.9	1.8
Response type		Local damage	Global deformation	Global deformation

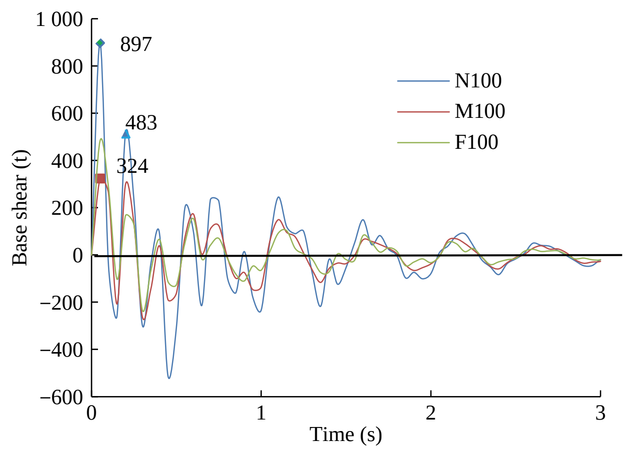

Figure 6 Response histories of base shear of the platform to the underwater explosion of 100 kg TNT

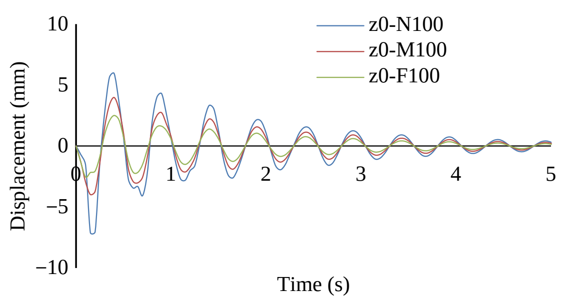

Figure 7 Response histories horizontal displacement at z = 0 of the platform to the underwater explosion of 100 kg TNT

As shown the base shear for the far distance explosion is less than both near and medium distance explosions. This is because of the influence of distance and loading surface

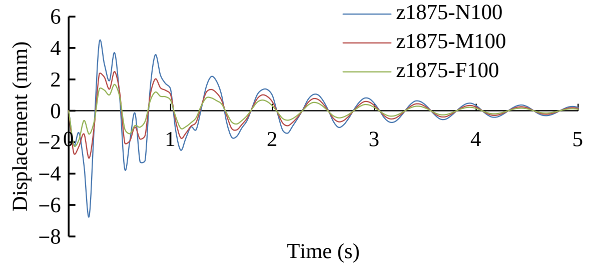

Figure 8 Response histories horizontal displacement at z = 1 875 of the platform to the underwater explosion of 100 kg TNT

simultaneously. In the near distance, the magnitude of pressure load is bigger than in the far distance.

Figure 9 shows time histories of the lateral displacement of the platform corresponding to different heights of 0 to −56.25 m for 50 kg TNT. As is shown, the displacements of platform reference points increase with time. The reason for this is that the explosion loading has a very short duration (generally a few milliseconds to dozens of milliseconds). From the 22 milliseconds (0.02 s) instant-on, significant deformation can be observed in particular in the vicinity of the blast level at −37.50 m elevation. Therefore, there is a higher probability of damage in a portion of the platform which is at the same level as the explosive material.

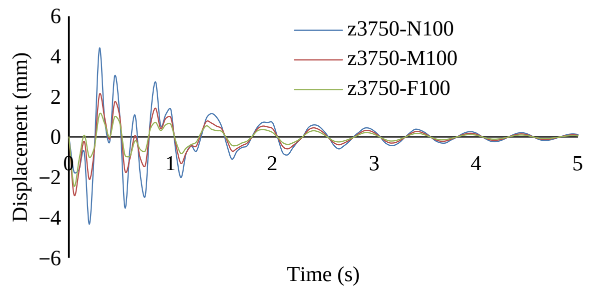

Figure 9 Response histories horizontal displacement at z = 3 750 of the platform to the underwater explosion of 100 kg TNT

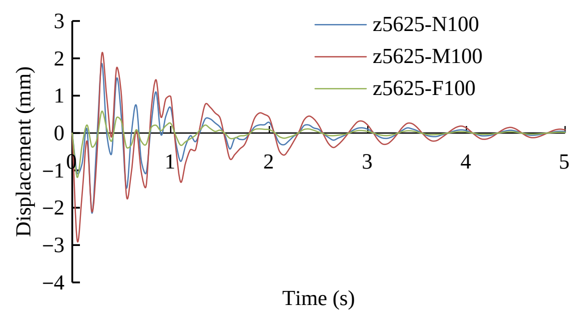

Figure 10 Response histories horizontal displacement at z = 5 625 of the platform to the underwater explosion of 100 kg TNT

The deformation modes of the platform under different explosive materials at the near, medium, and far-field have been presented in Figure 11.

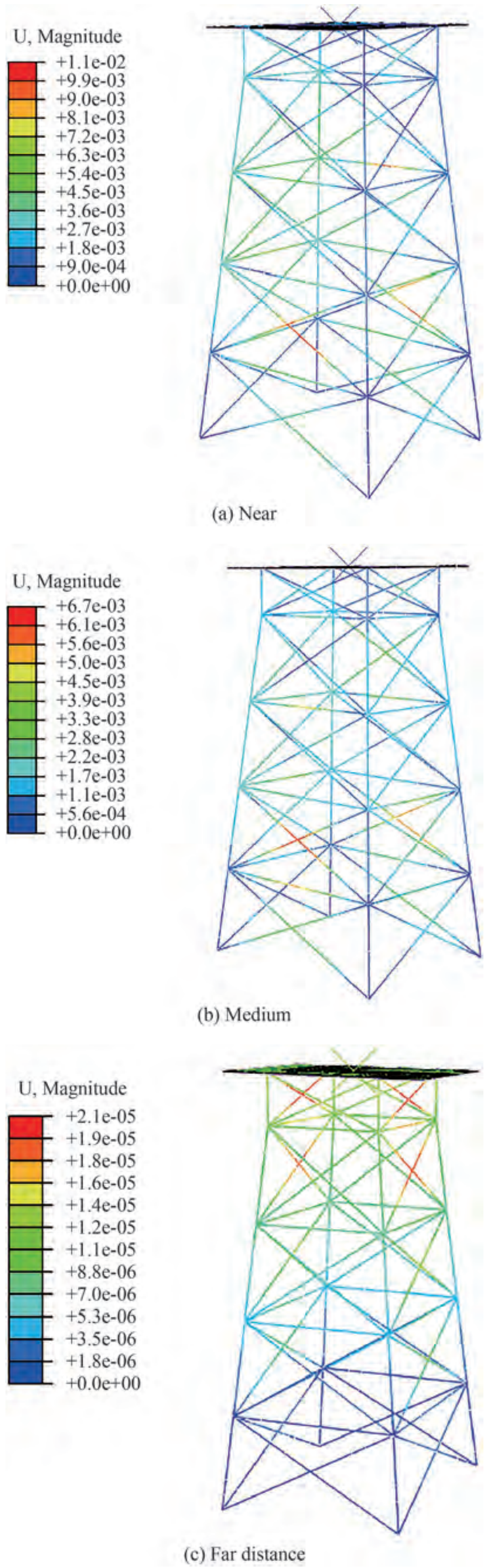

Figure 11 Deformation of Jacket at $t = 0.5$ s

6 Conclusions

In this research, the effect of underwater blast upon jacket platforms is studied by using the equivalent added mass model and solving the dynamic equations numerically. The explosive material has been placed in three locations as near, medium, and far stand-off distance from a platform. The obtained results may be summarized as follows:

1) In near-distance, the numerical modeling shows that a portion of the platform in the vicinity of the explosive material could be damaged in a very short time (50 to 70 s), and the deformation of this portion increases rapidly with time. The base shear is between 170 to 300 tons which are about 10 to 15 percent of the total platform weight. The base shear in the near-distance explosion is low because of the local effects of UNDEX. In this case, the whole platform may remain stable if it is designed against a progressive collapse phenomenon.

2) In the medium to far-distance explosions the whole platform experience UNDEX loading, so a global deformation will be produced. In this case base shear is large and may reach up to treble of total platform weight. The endurance time, in this case, is larger than near field explosions and if fixed support exists at the base of the platform, the platform may remain stable.

3) Because, in the design codes related to the jacket structures, the effect of the underwater blast is not considered, for the blast-proof design of jacket platforms it is necessary to perform first a risk analysis to specify the levels of threats and then use a method such as the one introduced in this article identify the vulnerable points of the platform so that the required strengthening can be determined.

Funding This research is supported and funded by Kharazmi University under the Ministry of Science and Technology (Tehran, Iran).

References

Abaqus documentation (2019) Dassault Systemes Simulia Corp

American Petroleum Institute (API) (2014) Recommended practice for planning, designing and constructing fixed offshore platforms-working stress design, 22th Edition, Chapter 17

Anwarul Islam AKM, Yazdani N (2008) Performance of AASHTO girder bridges under blast loading. Engineering Structures 30(7): 1922-37

Bangash MYH (1993) Impact and explosion analysis and design. Blackwell Scientific Publications 739

Biglarkhani M, Sadeghi K (2017) Incremental explosive analysis and its application to performance-based assessment of stiffened and unstiffened cylindrical shells subjected to underwater explosion. Shock and Vibration, 2017. https://doi.org/10.1155/2017/3754510

Cole R.H (1948) Underwater explosions. Princeton University Press

Continental Shelf Associates Inc (2004) Explosive removal of offshore structures - Information synthesis report, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS App., Study MMS 2003-070, 188

Det Norske Veritas (DNV) (2011) Structural design of offshore units (WSD Method), Section 8

Emamzadeh SSh, Ahmadi MT, Mohammadi S, Biglarkhani M (2015) Wave propagation due to underwater explosion for fluid-structure interaction problems. Journal of Marine Science and Application 14(3): 302-315

Geers TL, Hunter KS (2002) An integrated wave-effects model for an underwater explosion bubble. The Journal of the Acoustical Society of America 111(4): 1584-1601

Hao H, Tang EKC (2010) Numerical simulation of a cable-stayed bridge response to blast loads. Part II: Damage prediction FRP strengthening. Engineering Structures 32(10): 3193-205

Hicks AN (1972) The theory of explosion induced hull whipping. Naval Construction Research Establishment (NCRE), Dunfermline, Fife, Scotland, Report NCRE/R579

Hu Z-Y, Li S, Wang S-P, Zhang AM (2021) The role of fluid-structure interaction in pulsating bubble dynamics near a movable structure. Ocean Engineering, 238. https://doi.org/10.1016/j.oceaneng.2021.109650

Jayasooriya R, Thambiratnam DP, Perera NJ, Kosse V (2011) Blast and residual capacity analysis of reinforced concrete framed buildings. Engineering Structures 33(12): 3438-92

Jin Q, Ding G (2011) A finite element analysis of ship sections subjected to underwater explosion. International Journal of Impact Engineering 38(7): 558-66

Kalumuck KM, Duraiswami R, Chahine GL (1995) Bubble dynamics fluid-structure interaction simulation by coupling fluid BEM and structural FEM codes. Journal of Fluids and Structures 9, 861-883. https://doi.org/10.1006/JFLS.1995.1049

Li JC, Li HB, Ma GW, Zhou YX (2013) Assessment of underground tunnel stability to adjacent tunnel explosion. Tunneling and Underground Space Technology 35: 227-34

Lu Y, Wang Z (2006) Characterization of structural effects from aboveground explosion using coupled numerical simulation. Computers & Structures 84(28): 1729-42

Lu Y, Wang Z, Chong KA (2005) Comparative study of buried structure in soil subjected to blast load using 2D and 3D numerical simulations. Soil Dynamics and Earthquake Engineering 25(4): 275-88

Ma G, Zhou H, Chong K (2011) In-structure shock assessment of underground structures with consideration of rigid body motion. Journal of Engineering Mechanics 137(12): 797-806

Mair HU (1999a) Benchmarks for submerged structure response to underwater explosions, Shock and Vibration 6: 169-181

Mair HU (1999b) Hydrocodes for structural response to underwater explosions. Shock and Vibration 6: 81-96. https://doi.org/10.1155/1999/587105

Parisi F, Augenti N (2012) Influence of seismic design criteria on blast resistance of RC framed buildings: a case study. Engineering Structures 44: 78-93

Rajendran R, Lee JM (2009) Blast loaded plates. Marine Structures 22(2): 99-127

Ross M, Felippa CA, Park KC, Sprague MA (2008) Treatment of acoustic fluid-structure interaction by localized Lagrange multipliers: Formulation. Computer Methods in Applied Mechanics and Engineering 197: 3057-3079

Ross M, Sprague MA, Felippa CA, Park KC (2009) Treatment of acoustic fluid-structure interaction by localized Lagrange multipliers and comparison to alternative interface-coupling methods. Computer Methods in Applied Mechanics and Engineering 198: 986-1005

Son J, Lee HJ (2011) Performance of cable-stayed bridge pylons subjected to blast loading. Engineering Structure 33(4): 1133-48

Sprague MA, Geers TL (2006) A spectral-element/finite-element analysis of a ship-like structure subjected to an underwater explosion. Computer Methods in Applied Mechanics and Engineering 195: 2149-2167

Spranghers K, Vasilakos I, Lecompte D, Sol H, Vantomme J (2013) Numerical simulation and experimental validation of the dynamic response of aluminum plates under free air explosions. International Journal of Impact Engineering 54: 83-95

Tang EKC, Hao H (2010) Numerical simulation of a cable-stayed bridge response to blast loads. Part I: Model development and response calculations. Engineering Structures 32(10): 3180-92

Tian, L, Li ZX (2008) Dynamic response analysis of a building structure subjected to ground shock from a tunnel explosion. International Journal of Impact Engineering 35(10): 1164-78

Unified Facilities Criteria (UFC) (2008) Structures to resist the effects of accidental explosions

Wang H, Cheng YS, Liu J, Gan L (2016) The Fluid-Solid Interaction Dynamics between Underwater Explosion Bubble and Corrugated Sandwich Plate. Shock and Vibration, 2016, 6057437. https://doi.org/10.1155/2016/6057437

Wang W, Zhang D, Lu F, Wang SC, Tang F (2013) Experimental study and numerical simulation of the damage model of a square reinforced concrete slab under close-in explosion. Engineering Failure Analysis 27: 41-51

Wang Z, Lu Y, Hao H, Chong K (2005) A full coupled numerical analysis approach for buried structures subjected to subsurface blast. Computers & Structures 83(4-5): 339-56

Zakrisson B, Wikman B, Häggblad HA (2011) Numerical simulations of blast loads and structural deformation from near-field explosions in air. International Journal of Impact Engineering 38 (7): 597-612

Zhang A, Zeng L, Cheng X, Wang S, Chen Y (2011a) The evaluation method of total damage to ship in underwater explosion, Applied Ocean Research 33(4): 240-51

Zhang A, Zhou W, Wang S, Feng L (2011b) Dynamic response of the non-contact underwater explosions on naval equipment. Marine Structures 24(4): 396-411

Zhang S (2014) Numerical Simulation of Failure Modes of Concrete Gravity Dams Subjected to Underwater Explosion. Engineering Failure Analysis 36: 49-64