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Dynamic response of pipelines with various burial depth due to underwater explosion

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ABSTRACT

Underwater explosives that left in ports and harbors during World War II, which may not be inspected in reconnaissance surveys could threat submerged pipelines seriously. This paper developed a three-dimensional numerical model for dynamic response of pipelines induced by underwater explosion. Both FSI (Fluid-Structure interaction) and PSI (Pipeline-Seabed interaction) are taken into consideration simultaneously in current research. The proposed integrated model has been validated against experiment data available in previous literature. It has been found that the pipeline laid on the seabed tends to roll away from detonation rather than to deform in the pipeline section. The semi-buried pipeline is the most vulnerable due to combined action of reloading effect and trench constraint. Based on the numerical results, shallow buried installation is an effective method to enhance the anti-blast ability of submerged pipelines. The stress level of the pipeline increases slightly due to enhancement of the surrounding soil for shallow buried pipelines, while the integral lateral displacement and element pressure decrease with increase of burial depth.

1. Introduction

Marine pipelines are designed to bear various types of load like waves, currents and seismic load due to complex marine environment. Underwater mines and explosives that are left in harbor, ports and many other shipping routes after World War II may pose a threat to marine structures. Resistance design of submerged pipelines to accidental load is also crucial for production and transportation of offshore oil in the whole service life-cycle of pipelines because the accidental load like underwater explosion can lead to fatal damage to submerged pipelines.

Many explosion experiments have been carried out to investigate dynamic response of marine structures subjected to underwater explosion. kira et al., 1999 conducted experiments to study underwater explosion of spherical explosives by processing photographs and validate attenuation of the underwater blast wave. Rajendran and Narasimhan (2001) carried out underwater explosion experiments to investigate contact blast response of clamped circular plates. It was highlighted that the cylindrical shell structure was deformed as a joint result of primary shock and the bubble pulsation based on a small-scaled underwater explosion experiment (Hung et al., 2009). A critical distance of 10 times the radius of the charge to cylindrical shells was identified based on the small-scaled underwater explosion conducted by Li and Rong (2012). However, the small-scaled experiments of underwater explosion is incapable to simulate complete response of marine structures to blast loads. Moreover, most of the experiments focused on blast response of structures suspending in the water without consideration of PSI. An analytical model of dynamic response of metal tubed subjected to explosion was proposed based on blast experiments (Song et al., 2014) to forecast deformation distribution of cylindrical structures. Based on the experimental result and theoretical derivation, Zong and Lam (2000a, b) proposed an analytical model to calculate plastic strain and flexural deformation of a submarine pipeline to bubble pulsation. Kouretzis et al. (2007) derived analytical solution to strain response of flexible buried pipelines due to surface point blast, in which pipeline strains resulted subjected to P- and Rayleigh wave were calculated separately. The empirical formulas derived from explosion experiments are only capable to solving some specific engineering problems with many simplifications.

Massive energy is released by explosive detonation. The primary shock wave takes away more than half of the total energy, while the left is conveyed by the following bubble pulsation (Keil, 1961). The pressure stimulated by bubble pulsation is relatively lower (only 10%–20% that of primary shock), but is more effective for structure deformation due to long duration (Li and Rong, 2012). The destructive power of bubble pulsation to surface ships was highlighted by numerical results

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(Zhang et al., 2008; 2011). While effect of bubble pulsation is much smaller for the cylindrical structure below explosion (Hung et al., 2009). The peak pressure stimulated by bubble pulsation reaches about 15% the peak pressure of primary load for the sensor located 38 times the charge radius laterally (Li and Rong, 2012). Therefore, bubble pulsation, which is also a kind of reloading, will also affects the submerged pipeline in the near field of underwater explosion.

Since explosion experiments are hazardous to carried out except high cost, numerical methods turned out to be an excellent alternative to investigate blast response of submerged pipelines. Gong et al. (2000) adopted the coupled finite-element and boundary-element codes to assess submerged pipelines exposed to far-field underwater explosion neglecting the PSI. Lam et al. (2003) have investigated the dynamic response of a laminated pipeline simply supported on the rigid seabed subjected to far-field underwater explosion. Effect of bubble pulsation and PSI are certainly neglected in the above researches since reloading takes place as the water head above the charge is greater than half the stand-off and the seabed is treated as a rigid boundary. A structural integrity assessment of a pipeline subjected to underwater explosion was established by Monti et al. (2011), however PSI was dismissed. Van den Abeele and Verleysen (2013) simulates blast response of subsea pipelines suspending in the water and bubble pulsation is also neglected though bubble energy is not significant for the pipeline at the same depth of underwater explosion. In total, many numerical simulations of underwater explosion have been carried out to investigate dynamic response of submerged pipelines to blast loads based on FSI method. However, the seabed is simplified as a rigid boundary in the previous studies and effect of bubble pulsation is generally neglected. Actually, the blast wave propagating in the marine sediments also affects blast response of the submerged pipelines. Dynamic response of the pipelines due to underwater explosion will be underestimated neglecting interaction of seabed and pipelines.

In this study, a comprehensive hydro-mechanical model is proposed to investigate dynamic response of submerged pipelines subjected to underwater explosion. In the proposed model, FSI and PSI are studied simultaneously and effect of bubble pulsation is taken into consideration based on numerical technique. Primary theory, model parameters and numerical methods are introduced in the second section. Section 3 presents the validation procedure of the prototype model according to experimental data from previous research. In Section 4, a comprehensive study of dynamic response of submerged pipelines subjected to underwater explosion is carried out after sensitivity analysis of mesh size effect. Various motion patterns, deformation distributions and stress distributions of pipelines are presented due to various installation methods.

2. Material models and methodologies

2.1. Equations of state

2.1.1. The EOS for explosives

In this study, the TNT explosive is modeled via the Jones-Wilkins-Lee (JWL) equation of state (EOS), in which the pressure P is defined as a function of the relative volume, V and the initial energy per volume, E by an exponential function form as follow (LS-DYNA, 2007),

$$P = C_1\left(1 - \frac{\omega}{r_1 v}\right)e^{-r_1 v} + C_2\left(1 - \frac{\omega}{r_2 v}\right)e^{-r_2 v} + \frac{\omega e}{v} \tag{1}$$

where C_1, C_2, r_1, r_2, ω are material constants defined by experiments. And TNT and EOS parameters adopted in this paper are listed in Table 1.

Table 1
Material model and EOS parameters of TNT charge.

EOS:JWL
density $\rho = 1.63\ \text{g/cm}^3$
$C_1 = 3.738 \times 10^8 kPa$
$C_1 = 3.7347 \times 10^6 kPa$
$r_1 = 4.15$
$r_2 = 0.9$
$w = 0.35$
C-J detonation velocity (VOD): 6930 m/s
C-J energy/unit volume$6 \times 10^6 KJ/m^3$
C-J pressure: $2.1 \times 10^7 kPa$
$V_0 = 1$

2.1.2. The EOS for seawater

The Gruneisen EOS is adopted to simulate seawater for its excellent performance on handling the propagation of blast waves triggered by underwater explosion by incorporating a non-linear shock velocity and particle velocity relationship. Cavitation phenomena after underwater explosion can also be captured with Gruneisen EOS when simulating fluids under tension and compression.

With cubic shock velocity (u_s) - particle velocity (u_p), the Gruneisen EOS defines pressure for fluids under compression as (Souli, 2004):

$$p = \frac{\rho_0 C^2 \mu [1 + (1 - (\gamma_0/2))\mu - (a/2)\mu^2]}{[1 - (S_1 - 1)\mu - S_2(\mu^2/(\mu + 1)) - S_3(\mu^3/(\mu + 1)^2)]^2} + (\gamma_0 + a\mu)E \tag{2}$$

and for fluids under tension as:

$$p = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E \tag{3}$$

Where C is the intercept of the u_s-u_p curve, S_1, S_2 and S_3 are the coefficients of the slope of the u_s-u_p curve; γ_0 is the Gruneisen gamma and a is the first-order volume correction to γ_0; $\mu = \rho/\rho_0 - 1$ represents stress state of fluids. The parameters adopted for seawater (Kim and Shin, 2008)are listed in Table 2.

2.1.3. The EOS for ideal air

The air is modeled by null material with a linear polynomial EOS. The pressure P is expressed by:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \tag{4}$$

where E is internal energy per unit initial volume, C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are constants and $\mu = \frac{\rho}{\rho_0} - 1$, where $\frac{\rho}{\rho_0}$ is the ratio of current density to initial density. The parameters adopted for ideal gas are listed in Table 3.

2.2. Soil model

Dynamic response of marine sediment is very complex to predict due to the interaction of soil particles and pore water. An appropriate soil model is crucial for accuracy and rationality of simulation. The Mat 147 model developed by Federal Highway Administration (FHWA) is adopted in this study (Lewis, 2004; Reid et al., 2004). In the FHWA model, effects of strain softening, strain rate, kinematic hardening, and excess pore water have been taken into account. Moreover, the model

Table 2
Material model and EOS parameters of seawater.

EOS: Gruneisen
Density $\rho = 1.025$ g/cm3
Intercept of u_s-u_p curve, $C = 2417$ m/s
$\gamma_0 = 1$
$S_1 = 1.41$
$S_2 = 0$
$S_3 = 0$
First-order volume correction to gamma, $a = 0$
Initial internal energy per initial volume, $E_0 = 1890\ \text{kJ/m}^3$
$V_0 = 1$