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Numerical investigation of pore pressure effect on blast-induced pipeline-seabed interaction

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ABSTRACT

It is well-known that the pore water pressure plays an important role in the design of submerged structures since interaction of pore water and soil particles significantly affects surrounding soil behavior. However, the role of pore water within saturated soil was commonly neglected when estimating the blast-induced soil response. A pipeline-seabed interaction (PSI) model is established to simulate blast response of pipelines with consideration of pore water effect. The *u-p* approximation is incorporated into finite element method (FEM) to study dynamic response of pipelines buried in fully saturated soil subjected to underwater explosion. The Arbitrary Lagrangian-Eulerian (ALE)-Lagrangian algorithm is utilized to solve large deformation in the vicinity of underwater explosion. Test data from previous literature is adopted to validate the proposed model. Then, comparative analysis is carried out between the proposed model and the conventional model that excludes pore pressure. Numerical results from the proposed model are found to be distinctive from those obtained from the conventional model. Blast responses of the pipelines and soil are underestimated generally by the conventional approach. This contrastive analysis emphasizes pore pressure effect in engineering design of submerged pipelines.

1. Introduction

Submerged pipelines is the core facility in offshore oil industry and the pipeline is designed to sustain various loads in its service life cycle. However, the underwater explosives left in harbors and untapped oil field during wartime, which may not be inspected in reconnaissance surveys could pose a threat to marine structures.

Plenty of underwater explosion experiments have been carried out to investigate propagation of underwater blast wave and dynamic response of marine structures. A small-scaled experiments was carried out by Akio [1] to study underwater explosion of spherical explosives by processing photographs. The empirical formula was verified by the test data. Dynamic response of metallic material to underwater explosion is also the research hotspot. Rajendran [2] conducted underwater explosion experiments to investigate response of clamped circular plates to reveal deformation distribution and stress distribution of metal shell. Dynamic response of cylindrical shells with various stiffened methods was researched by underwater explosion in a water tank [3]. The critical distance of ten times radius of the explosion to cylindrical metal shell was indicated by Li [4] based on the small-scaled experiments of underwater explosion. However, the small-scaled experiment could help us to acquire preliminary understanding of underwater explosion, but it is incapable of simulating the complete response of marine structures to underwater explosion. Since the in-situ test of underwater explosion is hazardous and expensive, theoretical research based on numerical method turns out to be the best choice to investigate dynamic response of submerged pipelines subjected to underwater explosion.

FEM was adopted to analyze underwater shock problems by Young [5]. His work has presented the ability of FEM to solve high nonlinear problem. Gong [6] utilized a coupled FEM and BEM (Boundary-Element-Method) to assess the damage of pipelines exposed to underwater explosion neglecting effect of PSI. Blast response of the laminated pipeline, which is installed on a rigid boundary was studied [7]. In other situations, numerical simulations of underwater explosion is carried out to study the response of pipelines suspended in the water [3,4,8–10]. A structural assessment model of the pipeline integrity to underwater explosion was established [10] without consideration of PSI and pore pressure effect. In general, the seabed is mostly treated as single-phase medium or rigid boundary, which would neglect effect of PSI and pore pressure.

However, the pipelines will be installed on the seabed or shallowly buried. Dynamic response of submerged pipelines is affected by PSI. In addition, it has been demonstrated that initial air-filled void content of the soil and the effect of water content show great influence on soil behavior [11–13]. Incompressibility of the three-phase soil is enhanced

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significantly with higher soil saturation. Despite significance of pore water, it has been neglected in most of the predecessor's research when studying PSI problems. Blast energy attenuates slowest in the fully saturated soil [14,15]. Dynamic response of the pipelines buried in fully saturated soil is the researching focus in this paper, since they are more vulnerable than those buried in unsaturated soil.

In this study, pore water is taken into consideration by integrating *u-p* equations into FEM. A coupled ALE-Lagrangian algorithm, which is capable of solving large deformation in the proximity of detonation without loss of efficiency, is adopted to simulate underwater explosion. Theoretical method and material parameters are introduced in Section 2. Afterwards, the proposed model is validated against test data from previous literature in Section 3. Then Section 4 presents a comprehensive study of pore pressure effect on PSI subjected to underwater explosion. Comparative analysis of the proposed model and conventional model is performed to discuss various responses of submerged pipes subjected to underwater explosion.

2. Methods and models

2.1. Blast phenomenon and high explosive material

Explosion phenomenon takes place as original explosive material is breaking down into explosion product. Huge energy releases instantly, and a superheated, highly compressed gas bubble generates at the detonation point. The temperature of explosive production is thousands of degrees and the overpressure reaches up to 5 GPa [16]. Underwater explosion could result in damage of submerged structures.

Underwater explosion is applied in an indirectly way in this study. The high explosive burn and the Jones-Wilkins-Lee (JWL) equation of state (EOS) are adopted to model the detonation of TNT [17]. The JWL EOS defines the pressure P as a function of the relative volume, v and initial energy per volume, E using an exponential function form as follow,

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

where C_1, C_2, r_1, r_2, ω are material constants defined by experiment.

The air is modeled by null material with a linear polynomial equation of state, in which the pressure p is defined as follow:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E_0 \tag{2}$$

where E_0 is internal energy per unit initial volume, C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are constants. $\mu = \frac{\rho}{\rho_0} - 1$, where $\frac{\rho}{\rho_0}$ is the ratio of current density to initial density.

Material and EOS parameters adopted for TNT and air are listed in Table 1. The parameters ρ_{TNT}, V_D, P_{CJ} are the TNT density, detonation velocity and Chapman-Jouget volume, respectively.

2.2. Coupled hydro-mechanical model for explosion

The whole numerical simulation of underwater explosion can be divided into several processes, including explosive detonation, formation of explosive craters, propagation of the shock wave and interaction between soil and structures. A fully coupled method is adopted to simulate underwater explosion without being divided into several consecutive phases or regarding the output of one stage as the input of the next stage [18].

Blast response of pipelines is a highly non-linear problem both materially and geometrically. Non-linear contact also make solution procedure more difficult. A coupled ALE-Lagrangian algorithm is utilized to solve large deformation. Since Eulerian algorithm provides extensive ability for modelling problems like large distortions and deformation, the ALE formulation that can combine both merits of Lagrangian formulation and Eulerian formulation is applied to simulate the explosive, air and proximity of detonation.

Soil is considered as a multi-phase material, including soil particles and voids. Void of soil is filled with pore water and trapped air; soil particles establish the skeleton. The mechanical behavior of saturated soils subjected to dynamic loads [19] is governed by the interaction of the soil skeleton and pore fluid. Biot [20] originally proposed the theory of wave propagation in saturated porous media taking inertia of soil skeleton and pore fluid into account. Due to the difficulty of solving Biot's equations, various approximations [21,22] were developed to satisfy engineering applications. Among the various approximations, the *u-p* dynamic form stands out for its simpler form, fewer unknowns [23] and the pore pressure p can be derived from the formulation directly. Actually, it is not essential to solve the full Biot approximation until permeability of porous media reaches order of 10^{-3} m/s [24]. Therefore, the *u-p* approximation is utilized to govern the interaction of soil and pore water. The equilibriums of porous medium, equilibriums of fluid phrase and the mass conservation of fluid phase are expressed as follow,

$$\sigma_{ij,j} - \rho\ddot{u}_i - \rho_f\ddot{w}_i + \rho g_i = 0 \tag{3}$$

$$p_{,i} - \frac{\rho_f g_i}{k}\dot{w}_i - \rho_f\ddot{u}_i - \frac{\rho_f}{n}\ddot{w}_i + \rho_f g_i = 0 \tag{4}$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} + \frac{n}{K_f}\dot{p} = 0 \tag{5}$$

where σ_{ij} is total stress which is sum of effective stress σ'_{ij} acting on the soil skeleton and pore water pressure p. g_i is body force acceleration, u_i is displacement of the soil skeleton, w_i is the average fluid phase displacement, and n is porosity of soil material. K_f is bulk modulus of pore fluid. ρ_f and ρ represent pore fluid density and soil density respectively. It could be written as $\rho = (1 - n)\rho_s + n\rho_f$ in which ρ_s is density of the soil skeleton.

Soil skeleton displacement u_i, fluid displacement w_i, and pore water pressure p should be solved simultaneously. The fluid acceleration with respect to soil skeleton, $\ddot{w}$, can be neglected when the velocity of fluid, $\dot{w}_i$, is relatively small. Meanwhile, soil permeability is quite small for the porous media is regarded undrained under highly dynamic load. Substitute $\dot{w}_i$ in (4) into (5), and we can get a simplified *u-p* dynamic form based on the above assumptions. Soil skeleton displacement u_i and pore water pressure p are the only unknowns left. Finite element method (FEM) is adopted to solve the equations, and the spatial discretized form of the governing equations in the *u-p* form can be

Table 1
Parameters for TNT and ideal gas.

TNT									
ρ_{TNT} (g/cm^3)	V_D (m/s)	P_{CJ} (GPa)	C_1 (GPa)	C_2 (GPa)	r_1	r_2	ω	E_0 (kJ/m^3)	V
1.63	6930	21	373.77	3.747	4.15	0.9	0.35	6.0e+6	1
Ideal gas									
ρ_{air} (g/cm^3)	C_0	C_1	C_2	C_3	C_4	C_5	C_6	E_0 (kJ/m^3)	V
0.00129	0	0	0	0	0.4	0	0.4	250	1

Table 2
Parameters for pipelines and saturated soil (unit: g-cm-μs).

Muddy clay		Steel pipe		
Density	1.95	Density		7.8
specific gravity	2.75	Young's modulus		2.1
bulk modulus	0.03	Poisson's ratio		0.3
shear modulus	6.04×10^{-4}	Yield stress		0.004
peak shear strength angle	28	Tangent modulus		0.0025
cohesion	1.38×10^{-7}	Rupture strain		0.3
moisture content	0.35	Strain rate parameters	C	40
permeability	1×10^{-13}		P	5