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# Numerical study for dynamic response of marine sediments subjected to underwater explosion

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ABSTRACT

This paper developed a three-dimensional numerical model for saturated soil response induced by underwater explosion in marine environment. Unlike previous studies, three new features are included in the present model: (1) genuine detonation with real explosive materials; (2) coupled ALE (Arbitrary-Lagrangian-Eulerian)-Lagrangian algorithm for large seabed deformation; and (3) *u-p* formulation considering pore water pressure effect. The proposed explosion model is validated against experiment data available in the literature. Several parametric studies are carried out to investigate seabed response considering various soil types and TNT equivalent. Time series of total stress and pore pressure from sandy bed and clayey bed subjected to explosive loads are presented. Special attention is given to the distribution of peak total stress and pore pressure during propagation of blast wave. To facilitate engineering practice, a series of formulas for evaluating attenuation of peak total stress and pore water pressure are proposed.

## 1. Introduction

Seabed stability must be secured to ensure the safe operation of marine structures such as pipelines and platforms under oceanic accidental loads. Accidental load that may act on submerged structures includes wave load, tidal load or seismic load. In addition further load in emergency would possibly give rise to fatal damage. Underwater explosion, which may cause critical risk of foundation instability, is one of the most critical events threatening security of submerged structures. This study is intent to develop a novel numerical method to forecast saturated marine sediment response in dealing with such fatal risk.

Since explosion is a representative load in extreme conditions, it generates blast wave with high frequency, transient duration and extreme energy density. Marine sediments could be degraded or even destroyed by underwater explosion premeditatedly or accidentally. To avoid the great loss of explosive disasters, numerous studies on explosion have been carried out over the last few decades.

Yang (1997) has studied the response of buried shelters to blast load using a commercial FEM (finite element method) software, ABAQUS. In the study, a viscoelastic constitutive relationship was utilized to simulate soil behavior. Although the explosion effect has been simplified into time-dependent load, which obviously cannot reflect the real detonation process, the viscoelastic model gave a reasonable prediction of dynamic soil behavior under high loading rate. A comparative analysis between numerical simulation and experimental test of landmine explosion is carried out using numerical code named DYNA3D by Wang (2001). It has been demonstrated that the numerical method might underestimate the dynamic response of soil compared with experimental data in terms of maximum pore water pressure, displacement and velocity. Lu and Hanyga, 2005a,b,c analyzed dynamic response of layered porous media based on transmission and reflection matrices method coupling Biot's theory. A novel linear dynamic model was also proposed based on one energy approach for dynamic response of porous media saturated by immiscible fluids. Dynamic response of wave field was investigated by Johnson-Koplik-Dashen dynamic permeability model incorporating with Biot's theory. Feldgun et al. (2007) developed a coupled approach with a combination of variational principle and modified Godunov's method based on the fixed Eulerian mesh to simulate an axisymmetric explosion inside a pipeline. Although the discontinuity between pipeline and soil has been well captured, the pore water pressure of soil cannot be predicted due to fixed Eulerian mesh. In recent researches, Jayasinghe et al. (2013a,b, 2014) studied response of piles subjected to blast loading on commercial software LS-DYNA. The FHWA (Federal Highway Administration) constitutive relationship is utilized to simulate saturated soil

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response. However, the calculation of pore water pressure is based on an empirical relationship that is proportional to plastic volumetric strain, leading to omission of the interaction between soil and water.

Dynamic response of submerged structures subjected to underwater explosion is a hot topic that draws great attention in recent years and plenty of work dedicating to explore the protective effect of burial depth and concrete thickness has been carried out. An analytic method was proposed to analyze possible plastic deformation and failure mode by Gong et al. (2000) and Lam et al. (2001). Monte Carlo method was utilized to obtain bending moment distribution of pipeline. The double asymptotic approximation was implemented into FEM code ABAQUS to study response of laminated pipeline to underwater shock directly over it (Lam et al., 2003). However, the blast load and wave attenuation function are governed by empirical formula and effect of pore water is neglected. Lai (2007) studied response of submerged sphere shell to underwater explosion based on DAA (Double asymptotic approximation). In the study, response modes with different failure criterion and stand-off distance are concluded from parametric analysis. Hung et al. (2009) studied dynamic response of cylindrical structure subjected to underwater explosion and the 50 m critical distance was obtained by a series of model tests. A brief numerical simulation was carried out to verify experimental result simultaneously. Van den Abeele and Verleysen, 2013 utilized the display algorithm to simulate underwater explosion on the axial direction of a floating pipeline. The research findings are presented to facilitate the assessment of the safety of submerged pipelines in the vicinity of explosive. Koneshwaran et al. (2015a,b,c) studied blast response of underground tunnels with a SPH-FE coupled model. The FHWA model is adopted to simulate dry sand and the effect of pore water pressure is neglected spontaneously.

Overall, there have been extensive researches on dynamic response of ocean structure subjected to underwater explosion. However, the blast loading and wave attenuation are mostly governed by empirical formula other than material-charge coupled calculation. Furthermore, the influence of marine sediment on submerged structures is generally neglected. In addition, pore water pressure effect, which is crucial in the estimation of seabed instability, is not considered in previous researches. In this paper, a comprehensive numerical model is established based on *u-p* equations incorporated into FEM. This paper adopted a fully coupled technique incorporating ALE and Lagrangian algorithm to simulate large deformation and propagation of blast waves in marine soils. A brief description of background has been presented at the beginning of this paper. The second section introduces primary theory and numerical methods. Validation of prototype model according to available experimental data from TM 5-855-1 (Fundamentals of Protective Design for Conventional Weapons) is presented in Section 3. In Section 4, we carried out a comprehensive parametric analysis of explosion in marine sediments with various soil properties. Finally, a series of empirical equations for evaluating attenuation of peak total stress and pore water pressure are proposed to facilitate engineering practice.

## 2. Theoretical formulations

### 2.1. Coupled hydro-mechanical model for dynamic response

In this paper, the extended Biot dynamic equations are adopted for soil response under blast loading. The governing equations involve equilibrium of porous medium, equilibrium of fluid phrase and the mass conservation of fluid phase can be expressed as (Zienkiewicz et al., 1980),

$$\sigma_{ij,j} - \rho\ddot{u}_i - \rho_f\ddot{w}_i + \rho g_i = 0 \tag{1}$$

$$p_{,i} - \frac{\rho_f g_i}{k}\dot{w}_i - \rho_f\ddot{u}_i - \frac{\rho_f}{n}\ddot{w}_i + \rho_f g_i = 0 \tag{2}$$

$$\dot{u}_{i,i} + \dot{w}_{i,i} + \frac{n}{K_f}\dot{p} = 0 \tag{3}$$

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

In general, the governing equations should be solved simultaneously to consider the interaction of soil skeleton displacement $u_i$, fluid displacement $w_i$, and pore water pressure *p*. Neglect the fluid acceleration relative to the soil skeleton $\ddot{w}$ and substitute $\dot{w}_i$ in (2) into (3). Then a simplified *u-p* dynamic form (Zienkiewicz et al., 1980) is taken in this study, in which soil skeleton displacement $u_i$and pore water pressure *p* are the only unknowns to be solved through the governing equations. The spatial discretized form of the governing equations in the *u-p* form can be expressed as follows:

$$M\ddot{U} + C\dot{U} + KU - QP = F_U \tag{4}$$

$$G\ddot{U} + Q^T\dot{U} + S\dot{P} + HP = F_P \tag{5}$$

where *M* is global mass matrix, *C* is viscous damping matrix, *K* is stiffness matrix, *Q* is coupling matrix, *G* is dynamic seepage force matrix, *S* is compressibility matrix, and *H* is permeability matrix. *U* and *P* are the soil displacement and pore water pressure vectors, respectively. $F_U$ represents the effect of external forces and $F_P$ represents fluid flux. For more details about the *u-p* formulations, readers can refer to Zienkiewicz et al. (1980).

### 2.2. Material explosive model

Explosion pressure is applied to the porous marine sediments indirectly. The high explosive burn and the Jones-Wilkins-Lee (JWL) equation of state (EOS) are adopted to model the detonation of TNT (LS-DYNA, 2007). 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,

$$p = C_1\left(1 - \frac{\omega}{r_1 v}\right)e^{-r_1 v} + C_2\left(1 - \frac{\omega}{r_2 v}\right)e^{-r_2 v} + \frac{\omega e}{v} \tag{6}$$

where $C_1$, $C_2$, $r_1$, $r_2$, $\omega$ are material constants defined by experiment. 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 $\rho = 1.63$ g/cm$^3$ |
| $C_1 = 3.738 \times 10^8$ kPa |
| $C_2 = 3.7347 \times 10^6$ 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 ( $\psi_0$ ) : $6 \times 10^6$KJ/m$^3$ |
| C-J pressure: $2.1 \times 10^7$kPa |
| V = 1 |

An EOS is used to simulate overpressure subjected to detonation. And the burn fractions, F, controls the release of chemical energy in the high explosive burn material model. The burn fraction is taken as follow,

$$F = \max(F_1, F_2) \tag{7}$$