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Computational modeling and simulation for unexploded ordnance disposal problem at the seabed

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Abstract:*The main objective of our research is to contribute to the technique of unexploded bomb disposal such as an establishment of evacuation area based on computational mechanics. The computational simulation for undersea explosive problems was designed and demonstrated using Smoothed Particle Hydrodynamics schemes by HyperWorks (Altair®)–RADIOSS® software. The technique was to reveal the fragment behavior such as the amounts of charge and seabed soils. In this report, a study about the effect of a 50 kg general-purpose bomb and sea depth on the shock wave phenomena is presented. As a result, by conducting a series of computational simulations, it was observed and visualized that the fragment behavior significantly depends on charge amounts, depth of sea, and seabed soil.*

Key Word*:Unexploded Ordnance, Computational Simulation, Seabed Soil, SPH*

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I. Introduction

This experiment was conducted in Okinawa, where the only ground battle occurred in the Pacific War (The Greater East Asian War), with violent bombing and combat on the southern main island of Okinawa, where important points of the Japanese Army and Navy were located. Approximately 200,000 tons of bombs were detonated by the end of the war, including bombardment [1]. On the other hand, about 7% to 8% of fuses at the time were reported to have been unexploded because of malfunctions. This comprised about 5500 tons under US military rule and about 2000 tons after returning to the mainland of Okinawa on May 15, 1972. Although it has been processed, it is estimated that at least 70 years after the war, about 2000 tons of unexploded bomb (UXB) still remain buried [1]. According to the latest FY2018 results [2], 678 cases were found in public and private works including the carryover in FY2017, and the treated weight was 20.7 tons. However, it is estimated that it will take about 70 years to process all unexploded ordnance. Therefore, considering the situation not only in Okinawa but also in Japan, where urgent safety treatment of UXBs is required, (1) the improvement of discovery technology and (2) the development of treatment technology are important issues.

Until recently, the authors have developed the theoretical evacuation areas and actively reduced the evacuation area. This is to contribute to the development of unexploded ordnance safety disposal technology from a viewpoint based on computational mechanics. Hence, we construct a simple simulator for soil explosion problems using commercial finite element analysis software [3]. On the other hand, experiments using a high-speed camera optically captured how the shock wave from the explosion transmits and reflects through the unique Okinawan soil. The soil characteristics have been identified by comparing the experimental and numerical results and also confirmed the verification of the soil parameters' validity [4,5]. However, we have created a soil explosion problem simulator based on the Smoothed Particle Hydrodynamics (SPH) scheme and have conducted the computational experiments to visualize the fragment behavior generated during UXB explosion using particle imaging [6]. In addition, to propose the design and construction of a processing pit, which will actively reduce the evacuation areas, a numerical simulation with a protective wall using liner plate application was performed while the effect of suppressing fragments due to differences in exit shapes was also examined [7].

On the other hand, in underwater bomb disposal problem targeted in this paper, about 10% of the annual disposal results of unexploded ordnance have been processed on the seabed, and many of which were found on the seafloor and under the seabed during dredging work for securing routes in the ports. Many of these are transferred to the land and strictly managed in storage and processed at a treatment plant. However, if the UXB has a high degree of damage and there is a risk of explosion during movement, it cannot be transported and processed on land but must be processed in the seabed. In particular, with the treatment point at the center, a limited radius is provided over a wide range, such as "navigation prohibited area 300 m" and "incoming water prohibited area 3000 m," because the velocity of shock wave propagation in the sea associated with the explosion is approximately four times higher than in the air. There is a concern that shock waves generated during the processing of UXBs may cause (1) threats of undiscovered UXBs and mines, (2) damage to surrounding sea routes and port structures, and (3) effects on ecosystems, including surrounding marine life [8].

In this study, to clarify the effect of unexploded ordnance on the surrounding maritime and to establish theoretical evacuation areas based on the results of computational mechanics, we have constructed the seabed detonation problem simulator using commercial finite element analysis software. Using this simplified simulator, it is possible to demonstrate quantitatively through methods of computational mechanics the fragment behavior and shock wave propagation that will eject into the sea and the air as a result of the detonation. In this paper, a simple simulation model of the underwater bombing problem of unexploded ordnance has been constructed, and the fragment and underwater shock wave propagation behavior depending on the characteristics of air, seawater, and seabed soil was also discussed.

II. Computational Modeling for Undersea Explosion Problem

In this paper, the numerical modeling for undersea explosion problem has been designed using HyperWorks–RADIOSS (Altair®), and the computational simulation has been demonstrated. The analysis model subjects were as follows: (1) UXB (TNT), (2) seabed soil, (3) seawater, and (4) air, which were laid out using the measurements shown in Figure 1. The unit in this figure is cm. Here, because of symmetry of the problem, the analysis was carried out as a two-dimensional axisymmetric approximation of the quarter area in the *yz*- and *zx*-planes, taking the *z*-axis as the axis of rotational symmetry.In Figure 1, $z = 0$ is the boundary surface between undersea and seabed soil and $z = 600$ is also the boundary surface between air and undersea. The sea is positioned between $0 < z < 600$; soil, between $-600 < z < 0$; and air, between $600 < z < 800$. The base of the UXB, which is simply modeled as a sphere, is also placed as the origin of coordinate. The boundary shown by the dotted line in the figure is treated as a non-reflective boundary that does not inflow and outflow physical quantities [9]. In this report, we assumed the 50 kg general-purpose bomb. All regions of the

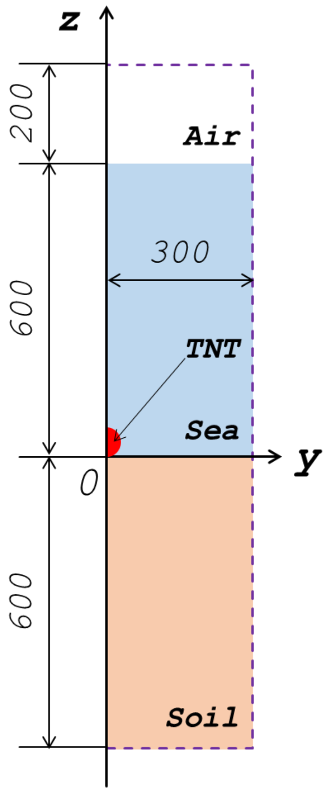

Fig. 1: Configuration of computational model for seabed soil, explosive (TNT), seawater, and air.

computational model were discretized by SPH elements that are 5 cm pitch; thus, the numbers of particles that correspond to explosive, sea, and seabed soil are 29, 327,465, and 327,488, respectively. The air was not discretized because of the characteristics of the software.

UXB. Material Type 5 of HyperWorks–RADIOSS (*M5; JWL EOS) was used for TNT, and the Jones-Wilkins-Lee equation of state (EOS) [10] was used to calculate the pressure generated by the expansion of the detonation products of the chemical explosive. The JWL EOS defines the pressure P_{JWL} as follows:

$$P_{JWL} = A\left[1 - \frac{\omega}{R_1 V}\right]\exp(-R_1 V) + B\left[1 - \frac{\omega}{R_2 V}\right]\exp(-R_2 V) + \frac{\omega E}{V}, \tag{1}$$

where A, B, R_1, R_2, and ω are the material constants; V is the relative volume of detonation product, and E is the detonation energy per unit volume with an initial value of E_0. The material parameters for TNT used in the present study [10] are as follows: A = 373.8 GPa, B = 3.747 GPa, R_1 = 4.15, R_2 = 0.95, ω = 0.35, E_0 = 6.0 J/kg.

Seabed soil. The Jahgaru [4] and Shimajiri–Mahji [5] are well known as widely distributed in the southern part of the main island of Okinawa. In this research, we created and evaluated a simplified version of an undersea explosion problem simulator implementing the dynamic characteristics of Shimajiri–Mahji. In the case of seabed explosion problem, it is easily understood that the seabed soil and explosive have prompted reactions and these fragments behave like fluid. Therefore, the explosive and the unique Okinawan soil are assumed to be factors that contribute to the material response as given by Johnson–Cook's type of constitutive equation (2) [11] and Mie–Gruneisen EOS (3) [12] as follows:

$$\sigma = (a + b\varepsilon^n)(1 + c \cdot \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}) \tag{2}$$

$$P = \frac{\rho_0 C_0^2 \eta}{(1-s\eta)^2}\left[1 - \frac{\Gamma_0}{2}\eta\right] + \Gamma_0\rho_0 e, \quad \eta = 1 - \rho_0/\rho \tag{3}$$

whereσ, ε, and $\dot{\varepsilon}$ are the material stress, strain, and strain rate, respectively. The terms a, b, c, n, and $\dot{\varepsilon}_0$are the material constants associated with the Shimajiri–Mahji. Next, in Eqn. (3), P, ρ_0 and e are the pressure, the initial density, and the initial energy per unit reference volume, respectively. Similarly, C_0, s, and Γ_0 are the bulk speed of sound, the linear Hugoniot slope coefficient, and Gruneisen's gamma at the reference state, respectively. The material parameters for seabed soil [5] used in this paper are as follows: $a = 120$ kPa, $b = c = 0$, $n = 0.01$, $\rho_0 = 1740$ kg/m^3, $C_0 = 2570$ m/s, $s = 1.73$, $\Gamma = 0.75$. The elastic constants of Shimajiri–Mahji are given as follows: Young's modulus E = 12.3 MPa, Poisson's ratio ν = 0.495.

Seawater. Material Type 6 of HyperWorks–RADIOSS (*M6; Hydrodynamic viscous) was used for the seawater. This material model must be used with an EOS. The polynomial EOS used in this study is expressed as follows:

$$P = A_0 + A_1\mu + A_2\mu^2 + A_3\mu^3 + (A_4 + A_5\mu)E_0, \quad \mu = \rho/\rho_0 - 1 \tag{4}$$

where E_0 is the initial energy per volume. The term μ is the compression of the material defined by the parameter with ρand ρ_0, the current and initial densities of the material, respectively. The air assumed to be an ideal gas was modeled by setting $A_0 = A_1 = A_2 = A_3 = 0$ and $A_4 = A_5 = \gamma - 1$, where γ is the ratio of specific heat. In this study, the standard material constants of air $\gamma = 1.403$, $\rho_0 = 1.29$ g/cm^3 are used [12].

III. Computational Result and Discussion

The time variations of particle velocity distribution are shown in Figure 2. It was confirmed that the distribution radially spreads to undersea and seabed soil from the detonation source, which corresponds to the UXB. Furthermore, it was also observed that the propagation velocity of the seabed soil was faster than the seawater, because the sound velocity of the soil was greater than the undersea. Here, in the computational results, it can be confirmed that the particle velocities propagating in both media (seawater and seabed soil) exceed the speed of sound, so that they propagate as shock waves. The time histories of the particle of maximum velocity are shown in Figure 3. The black and red solid lines denote the open air [7] and the seawater, respectively. In addition to the initial particle velocity, the latter particle velocity was larger in open air than in seawater because the density of seawater is 1000 times different than the density of air. Furthermore, it can be confirmed that the decay of the velocity is more remarkable in seawater. These results show that the seawater can prevent the fragments.

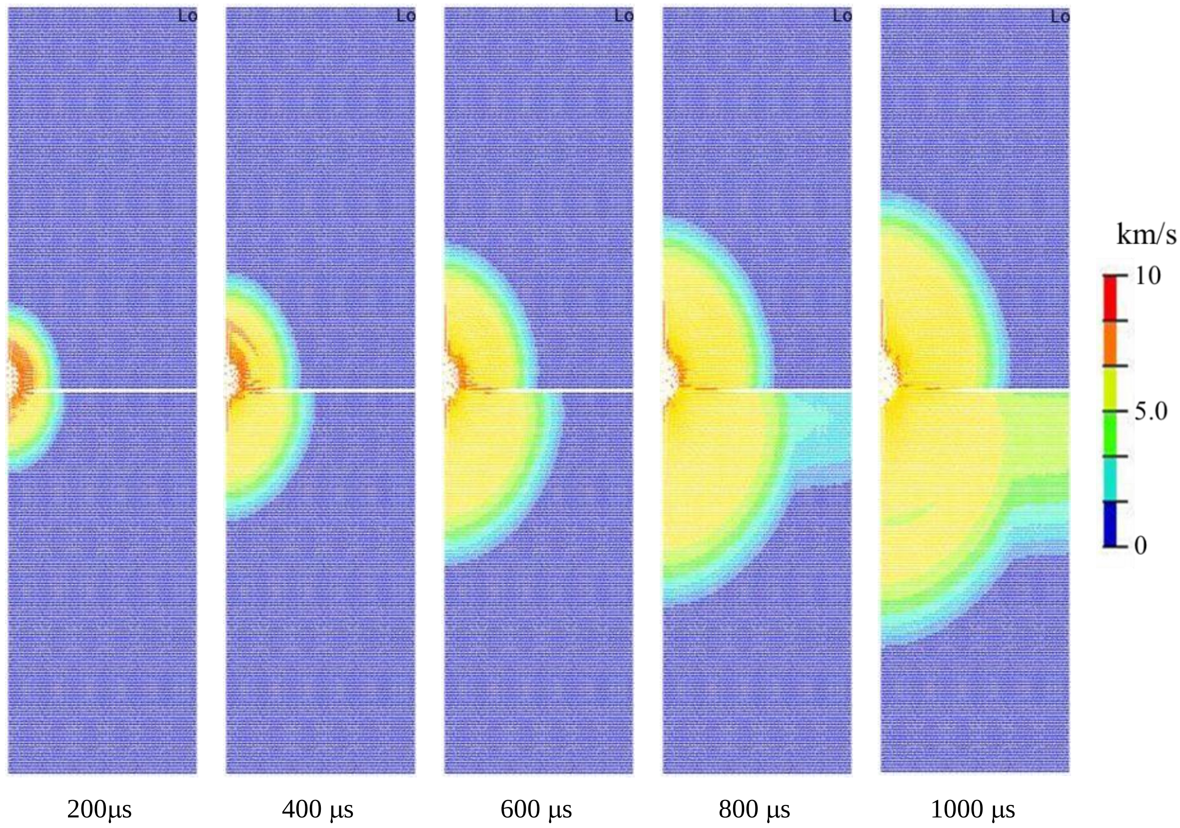

Fig. 2: Particle velocity distribution at each computational time step.

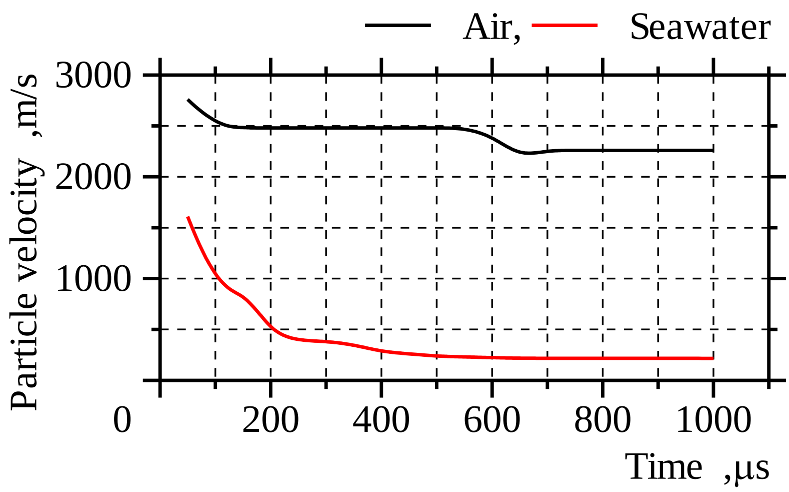

Fig. 3: Time history vs maximum particle velocity; black and red lines denote the air and the seawater, respectively.

IV. Conclusion

In this study, to elucidate the effect of unexploded ordnance on the surrounding maritime and to establish theoretical evacuation areas based on the results of computational mechanics, we have constructed the seabed detonation problem simulator using commercial finite element analysis software. First, the simple simulation model of the underwater bombing problem of unexploded ordnance was demonstrated. The fragment and underwater shock wave propagation behavior depending on the characteristics of air, seawater, and seabed soil has also been discussed. We visualized the particle velocity distribution depending on the density of the seabed soil and seawater. In addition, the decay of the particle velocity as more remarkable in seawater was confirmed. These results suggest that the seawater can prevent the fragments compared with surface explosion corresponding to open air. Thus, the computational simulation of the fragment behavior, which depends on different charge of the explosive, bomb shape, and depth of sea, is an ongoing research work.

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