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A Computational Simulation for Explosive Ordnance Disposal

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Abstract. In order to clarify the characteristic behavior such as shockwave propagation, dispersion of sand and the crater depth due to explosive ordnance disposal, the finite element models of soil, surrounding air and explosive have been constructed based on HyperWorks-RADIOSS (®Altair) software. By conducting a series of numerical simulations, it has been observed the effect of explosion on the crater depth and diameter, overpressure exerted on sand and the surrounding air. These results based on the computational mechanics are useful data for setting the evacuation area and its distance associated with an explosive ordnance disposal.

Introduction

Even today, nearly 70 years after the end of World War II, there are an estimated 2,200 tons of unexploded ordnance buried in the ground in Okinawa, the site of the only ground battle fought in Japan during the War [1]. According to fiscal year 2011 records, there were 887 discoveries of unexploded ordnance during public and private-sector construction work, and 38.1 tons were disposed of [2]. However, it is estimated that, even if disposal continues at this pace, it will take around 50 years to get rid of all of the unexploded ordnance. Therefore, this situation in Okinawa Prefecture calls for the earliest possible disposal of unexploded ordnance, and two key technical issues when considering this is the (1) improvement of detection technology and (2) development of disposal technology, with a prerequisite of ensuring safety. There are problems with the current process of disposing unexploded ordnance, including the fact that, due to an establishment of evacuation zones based on rules of thumb, economic activity inside such zones is restricted. Recent examples of disposal include a 250 kg bomb at Sendai Airport [3] and a 500 lb incendiary bomb at Moto-Akasaka [4], which are fresh in people's memories. These examples proved that when unexploded ordnance are found in densely populated urban areas, public transportation and various economic activities are stopped according to the above-mentioned rules of thumb, incurring enormous economic losses. Therefore, in order to contribute to the development of disposal technology, this research constructed an underground detonation problem simulator using general-purpose finite element analysis software, with the objective of establishing theoretical evacuation zones based on the results of computer experiments. Using this underground detonation problem simulator, it is possible to demonstrate quantitatively through methods of computational mechanics the amount of soil that will eject into the air as a result of the detonation when disposing of unexploded ordnance and the size of the blast associated with shock wave propagation through the air. As an implementation of the underground detonation problem simulator and analysis of its results, the influence that differences in the buried location and amount of gunpowder in unexploded ordnance have on crater depth and radius was investigated. This investigation is presented in this report.

Computational model

In this research, a numerical simulation model for underground detonation problems was created using the general-purpose finite element analysis software, HyperWorks-RADIOSS (®Altair), and analyses were carried out. The subjects of the analysis model were as follows: (1) soil, (2) air, and (3) explosive (unexploded ordnance), and they were laid out using the measurements shown in Figure 1. Here, due to symmetry of the problem, the analysis is carried out as a two-dimensional axisymmetric approximation of half the region in the yz-plane, taking the z-axis as the axis of rotational symmetry. In the figure, $z = 0$ is the boundary surface between air and soil, and air is positioned between $0 < z < 2000$ and soil between $-1400 < z < 0$. Also, in the figure, D.O.B.$= d$ is the depth of a buried, and the unexploded ordnance is modeled as a cylindrical shape with a circular upper base centered on $(0, -d)$. The boundary shown by the dotted line in the figure is treated as a non-reflective boundary that does not reflect physical quantities.

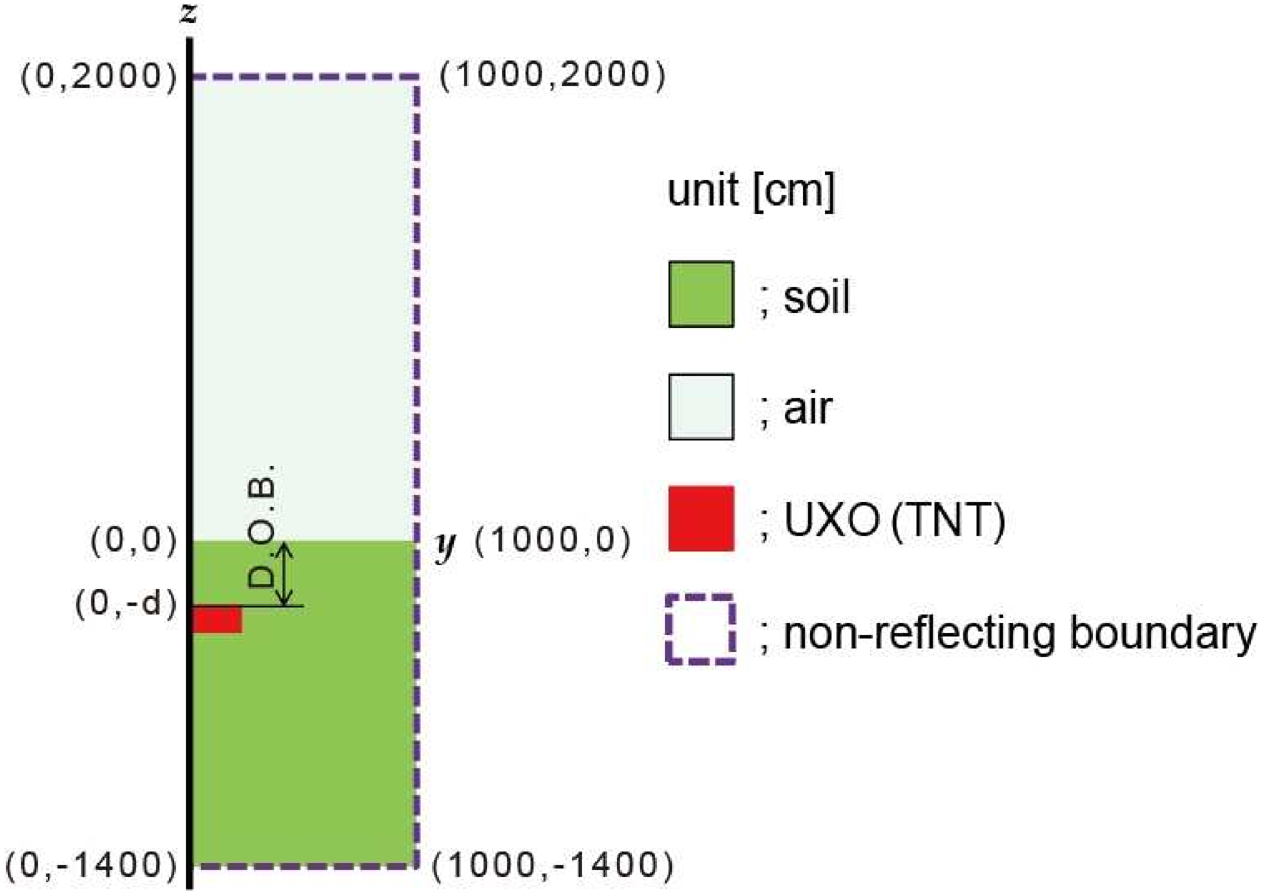


Fig.1 Computational model.

(1) Soil The soil in the southern part of the main island of Okinawa is known as *Jahgaru* [5] and is derived from marl deposits coming from the continent since ancient times. This soil consists of extremely fine argillaceous particles, and the mechanical characteristics of the soil are known to vary widely according to differences in underground moisture content. However, there appears to be no reported examples of the dynamic characteristics of the soil that are required for this research. Therefore, in this research, it was decided to create and evaluate a simplified version of an underground detonation problem simulator implementing material characteristics that have already been reported. Here, constitutive equations applicable to materials that exhibit volumetric plastic deformation, such as concrete, rock, and soil, are introduced. The constitutive equation introduced to elastic solid is used as follows:

$$\sigma_{ij} = \frac{E}{2(1+\nu)}\varepsilon_{ij} + \frac{E\nu}{(1+\nu)(1-2\nu)}\delta_{ij}\varepsilon_{kk} \qquad (1)$$

where E and ν are the Young's modulus and Poisson's ratio, respectively. δ_{ij} Kronecker delta. σ_{ij} and ε_{ij} denote stress and strain tensor, respectively. Then, Material Type 21 of HyperWorks-RADIOSS (*M21; Drucker-Prager for Rock and Concrete) is used as follows:

$$f = J_2 - (A_0 + A_1 P(\varepsilon_v) + A_2 P(\varepsilon_v)^2 \tag{2}$$

where f indicates the Drucker-Prager yield criterion [6]; A_0, A_1 and A_2 are material constants related to the characteristic of soil. P, J_2 are the hydrostatic pressure and the deviatoric stress invariant, respectively. P depends on the volumetric strain $\varepsilon_v \cong \varepsilon_{kk}$ as shown in Figure 2. The material parameters for soil used in this study are as follows [7]: $E = 191.4$ MPa, $\nu = 0.495$, $A_0 = 3.4 \times 10^{-13}$, $A_1 = 7.0 \times 10^{-7}$, $A_2 = 0.3$.

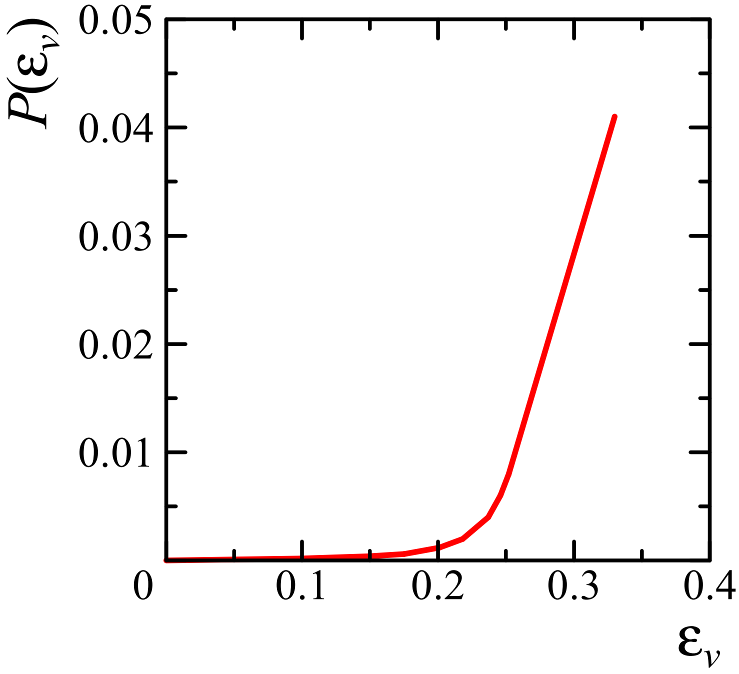


Fig.2 Pressure versus volumetric strain ε_v relationship.

(2) Air Material Type 6 of HyperWorks-RADIOSS (*M6; Hydrodynamic viscous) is used for the air. This material model must be used with an equation of state (EOS). The polynomial EOS is used in this study as follows:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)e_0 \tag{3}$$

where e_0 is the internal energy per volume. The compression of the material is defined by the parameter $\mu = (\rho/\rho_0) - 1$ with ρ and ρ_0 being the current and initial density of the material, respectively. The air assumed to ideal gas is modeled by setting $C_0 = C_1 = C_2 = C_3 = 0$ and $C_4 = C_5 = \gamma - 1$ with γ is the ratio of specific heat. In this study, the standard material constants of air $\gamma = 1.403$, $\rho_0 = 1.29\ \mathrm{g/cm^3}$ are used.

(3) Explosive Material Type 5 of HyperWorks-RADIOSS (*M5; JWL EOS) is used for TNT and the Jones-Wilkins-Lee EOS is 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:

$$P_{JWL} = A\left[1 - \frac{\omega}{R_1 V}\right]\exp(-R_1 V) + B\left[1 - \frac{\omega}{R_2 V}\right]\exp(-R_2 V) + \frac{\omega e}{V} \tag{4}$$

$$P_{CJ} = \frac{\rho_0 D^2}{\gamma + 1} \tag{5}$$

where $\mathrm{A}, \mathrm{B}, \mathrm{R}_1, \mathrm{R}_2$ and ω are the material constants, V the relative volume of detonation product, e the detonation energy per unit volume with an initial value of e_0. P_{CJ} indicates the Chapman-Jouguet Pressure depending on the initial density ρ_0 of TNT and the detonation velocity D. The material parameters for TNT used in the present study are as follows [7]: $\mathrm{A} = 373.8\ \mathrm{GPa}$, $\mathrm{B} = 3.747\ \mathrm{GPa}$, $R_1 = 4.15$, $R_2 = 0.95$, $\omega = 0.35$, $e_0 = 6.0\ \mathrm{J/kg}$, $\rho_0 = 1.63\ \mathrm{g/cm^3}$, $D = 6930\ \mathrm{m/s}$. As a subject of the analysis, TNT exhibits solid/fluid behavior when it detonates, and soil also shows solid/fluid behavior with destruction. Therefore, in this research, all subjects of the analysis, including air, are analyzed as the elements based on the Arbitrary Lagrangian Eulerian (ALE) [8] formulations.

Computational result

As an example of the calculation results, the effect of the difference of TNT volume, (a)250 kg and (b)3.29 kg on the computational result are shown in Figure 3. This figure show the density distribution with time evolution when D.O.B.=200 cm. In case of TNT=250 kg, it is seen that a crater of radius approximately 2.5 m and depth approximately 5.4 m is formed at $t = 50$ ms. It also confirms that, as a result, all of the soil that was on top of the unexploded ordnance is blown off. In case of TNT=3.29 kg, in contrast, it is observed that the crater is not formed because the force of an explosion is smaller than TNT=250 kg. And then, the high density region due to positive ground shock pressure generated by the explosion is widely distributed in soil associated with the difference of TNT volume.

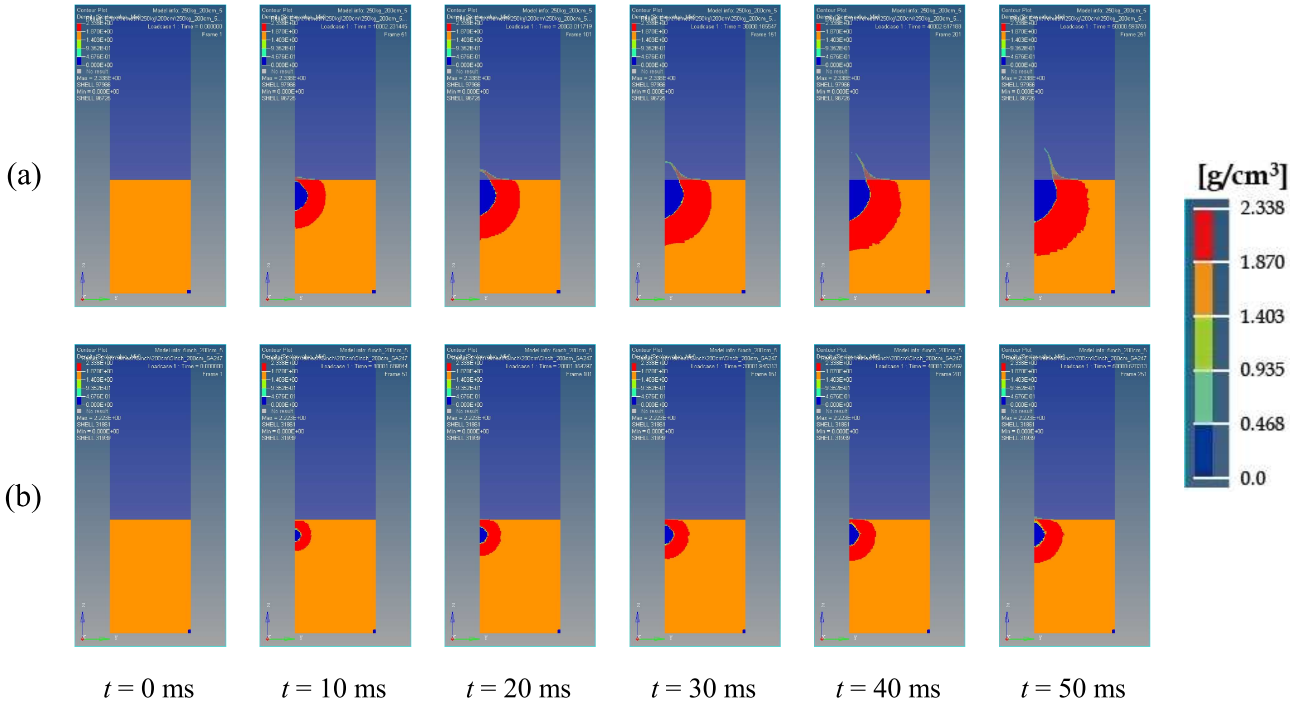
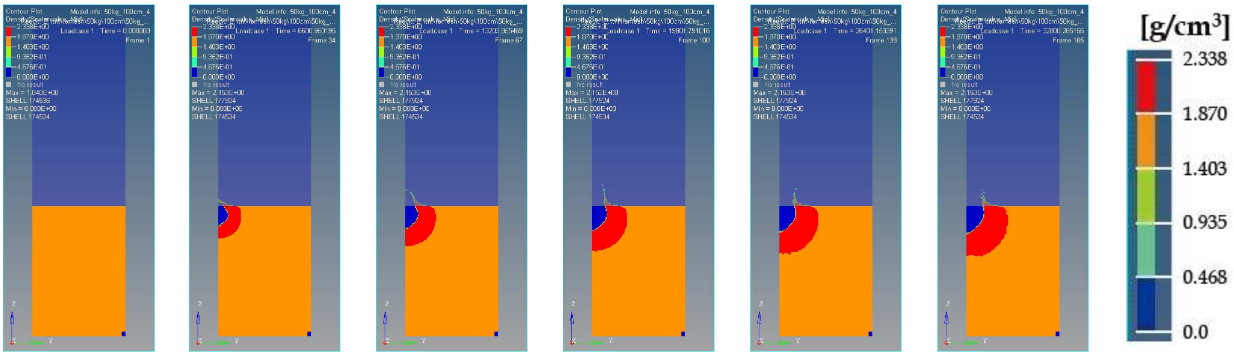
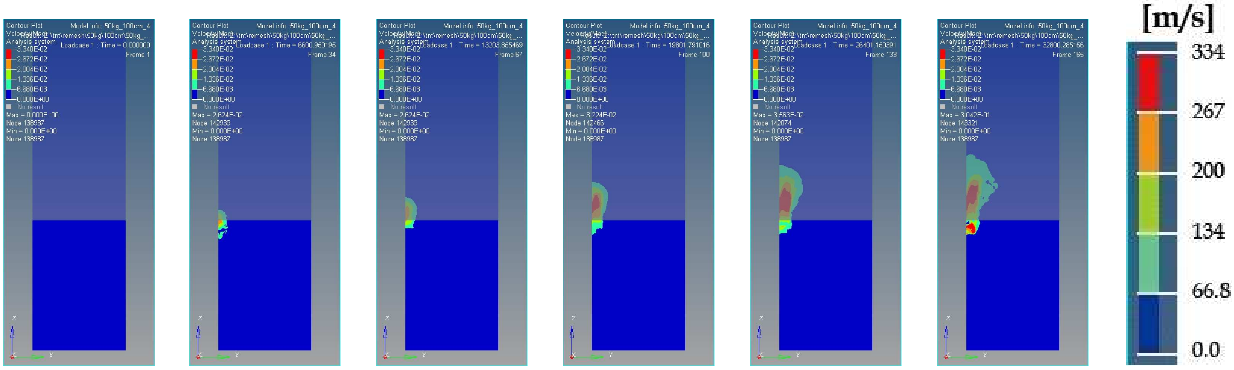


Fig. 3 Time variation of density distribution for (a) TNT=250 kg and (b) TNT=3.29 kg at D.O.B.=200 cm.

The density and gas velocity distribution corresponding to TNT=50 kg and D.O.B.=100 cm are shown in Figure 4. It is seen that a crater of radius approximately 1.8 m and depth approximately 2.8 m is formed at $t = 32.8$ ms. As a same result the case of TNT=250 kg and D.O.B.=200 cm, it is also observed that all of the soil on top of the unexploded ordnance is blown off. The figure 4 (b) confirms



(a) Density distribution



(b) Gas velocity distribution

Fig. 4 Time variation of (a) density and (b) gas velocity distribution for TNT=50 kg at D.O.B.=100 cm.

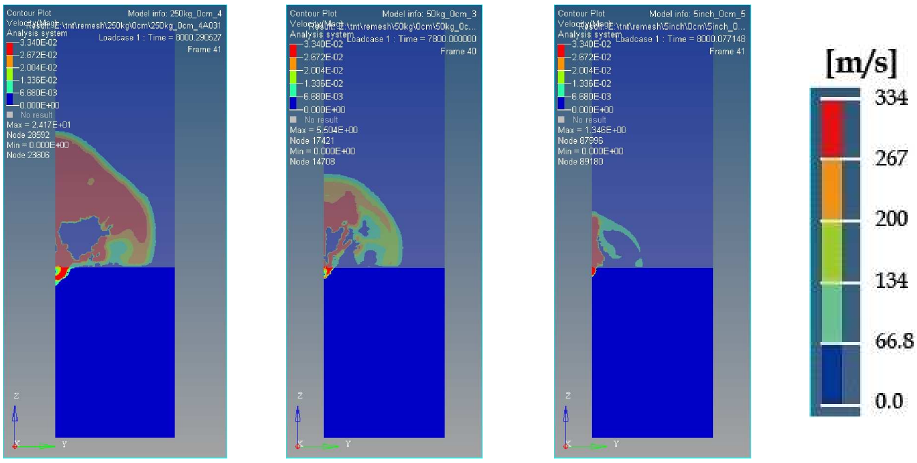


Fig.5 The gas velocity distribution for different volume of TNT at D.O.B.=0 cm in $t \cong 8.0$ ms.

that a region of extremely fast gas velocity exceeding the speed of sound in air (approximately 334 m/s) moves into the sky along with the explosion and propagates radially over a wide area. The effect of the difference of TNT volume, (a)250 kg, (b)50 kg and (c)3.29 kg on the gas velocity distribution are also shown in Figure 5. All the computational results indicate D.O.B.=0 cm namely the ground level. It can be observed a very fast gas velocity area is widely distributed with an increase in the amount of TNT and extremely short time. Because this velocity distribution is related to the characteristic behavior of shock wave propagation, these data are extremely important in evaluating the effects on surrounding structures, such as shattering of glass windows.

Conclusions

In this study, to clarify the characteristic shock wave propagation and fragments according to underground explosive, we have constructed a computational model of soil, air and unexploded ordnance using commercial Finite Element Analysis solver. By conducting a series of computational simulations, we can obtain the following results:

i) We can visualize the gas velocity distribution contributed to shock wave propagation and can also do the density distribution associated with the ground shock pressure.
ii) The process of crater formation and the behavior of fragments according to underground explosive has been observed depending on the difference of TNT volume and the depth of buried unexploded ordnance.

The computational results in this study, however, are very simplified because the dynamic characteristic of soil *Jahgaru* is unknown. An investigation of the dynamic characteristic feature with respect to *Jahgaru* is now in progress. A design of the barricade, the evacuation area and its distance associated with an explosive ordnance disposal becomes possible using the computational simulation based on the experimental data without depending on rule of thumb.

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