Research paper

Investigation on the attenuation effect of the high-explosive ground surface detonation

Masahide Katayama*†, Atsushi Abe*, Atsushi Takeba*, Shiro Kubota**, Tomoharu Matsumura**, Kunihiko Wakabayashi**, and Yoshio Nakayama**

*ITOCHU Techno–Solutions Corporation (CTC)
3–2–5, Kasumigaseki, Chiyoda–ku, Tokyo 100–6080, JAPAN
Phone : +81–3–6203–7425
† Corresponding author : masahide.katayama@ctc-g.co.jp

**National Institute of Advanced Industrial Science and Technology (AIST)
1–1–1, Higashi, Tsukuba, Ibaraki 305–8568, JAPAN

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Abstract

After reviewing the characteristics of 3-dimensional (3-D) FCT (Flux Corrected Transport) Euler scheme from the viewpoints of both strengths and limitations, this paper certifies that the present method enables us effectively to simulate the distance attenuation effect of the peak overpressure and the impulse after the high-explosive (HE) detonation on the ground surface up to around the scaled distance of $20\,m \cdot kg^{-1/3}$ by comparing several experimental results including domestic and foreign data. Especially, the present methodology is applicable to considerable large-scale problems even by using current ordinary personal computers, and it also suggests the feasibility of complicated 3-D fluid-structure interaction analyses in the very near future.

Keywords : attenuation effect, flux corrected transport, ground surface detonation, scaled distance, TNT

1. Introduction

As is well known, the spatial attenuation process of the peak overpressure of the blast wave in the air has been investigated through a lot of experimental tests of the TNT detonation on the ground surface by domestic and various international organizations for these several decades, in order to evaluate the secure distance from the explosion source of high-explosives (HE)[1)-3)].

At the same time, a number of numerical trials to simulate the present physical phenomena have been also conducted by many researchers, making use of purely numerical or engineering (empirical) approaches, as the above-mentioned experimental results were referred to perpetually. However, in the case of purely numerical method, especially when using Eulerian frame of reference although it is effective to the gas dynamics analysis in general, they have suffered from the fact that the whole scale of the target area is much larger than the area of the unburned HE.

Our research group has also conducted purely numerical simulations by using both 1-D (spherical symmetry) multiple-material Eulerian scheme to model a multiphase system and 3-D Flux Corrected Transport (FCT)[4),5)] Eulerian scheme to model a rigid ground shape[6),7)]. There was nine-year interval between these two studies, but we had still considerable difficulties to switch from 1-D to 3-D calculations, because the advancement of the computer resources for the period was not so remarkable for the purpose.

On the other hand, there have become rapidly popular 64-bit personal computers (PCs) after around 2010, additionally we have been able to make use of more than 10 GB main memories from the viewpoint of a computer hardware and to utilize an application software compliant to the 64-bit calculation, as well as the operating system (OS). Consequently, some significant 3-D calculations have come within the range.

In this study, by using a current ordinary PC, 3-D blast analyses for the large-scale area, which could not be worked out ten years ago even using massively parallel processors, were performed by a FCT Eulerian solver (so-called “Ideal Gas” Eulerian solver in the hydrocode of ANSYS AUTODYN), and the results will be compared and investigated with three kinds of experimental test data of TNT detonation on the ground surface up to enough far away from the center of detonation practically. The phenomena can be assumed to be almost axisymmetric, and it is not necessary for the 3-D analysis to be carried out. But, the present analysis is intended to be a feasibility analysis of more complicated physical model, like taking account of the ground shape effect, the interaction with structures, etc. From the viewpoint of the investigation and assessment on the security of humans and structures, the range up to around $20\,\mathrm{m\cdot kg^{-1/3}}$ by the scaled distance is of great importance practically.

2. FCT[4), 5)] Euler scheme

Some ingenuity is indispensable to reproduce the steep spatial gradient in the vicinity of the shock wave front where the physical properties vary approximately discontinuously. In order to satisfy such a requirement by using the finite difference method, it is necessary to reduce numerical diffusions and numerical oscillations simultaneously. Generally speaking, if we applied any low-order differential scheme to the spatial direction, the physical properties which should be preserved could not maintain their spatial profiles owing to the numerical diffusion, and in the meantime, if we did any high-order scheme, we might sometimes encounter negative physical properties caused by the numerical oscillation. The FCT scheme was proposed and developed to reduce such problems numerically.

The FCT scheme consists of the “transport step” and the “correction step”, and it is the basic concept that the numerical diffusion errors yielded in the transport step are adjusted in the correction step.

Figure 1 shows a typical absolute pressure history at a certain position distant from the HE explosion source on the rigid ground surface by using the FCT solver of ANSYS AUTODYN. It should be noted that a numerical (non-physical) undershot pressure is reduced considerably but is still evaluated, which was caused by the above-mentioned “correction step”, even when using the FCT method.

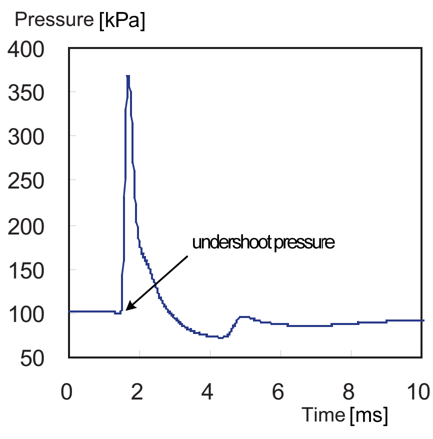

Figure 1 An example estimating undershoot pressure before the peak value.

In addition, there exist other disadvantageous problems in ordinary FCT schemes like : i) can use only a single material, ii) can only use the ideal gas equation of state, iii) can only use the rectangular grids, etc. Through the present study, the asymmetric peculiarity caused by the advection calculation rose up to the surface, and it will be investigated in the “Discussions” of section 6.

3. Reference experiments

In 1964, Kingery et al. compiled[1)] the relation of the scaled peak overpressure as a function of the scaled distance based on the airblast data taken on four large (about 5-500 ton, hemispherical charges) TNT surface bursts which were conducted in Canada between 1959 and 1964. The experimental results were recorded on these tests by the representatives from the United States, Canada, and the United Kingdom.

In 1984, Kingery et al. re-fitted[2)] the information on a) scaled time of arrival, b) peak overpressure, c) scaled positive phase duration, and d) scaled positive phase impulse. At the same time, through the calculational methods they added[2)] the information on e) reflected pressure, f) reflected impulse, and g) shock front velocity.

Meantime, Nakayama et al. compiled[3)] the relation of the scaled peak overpressure as a function of the scaled distance based on the airblast data taken on five (about 25-200 kg charges) TNT surface bursts which were conducted in Japan between 1984 and 1986. They also conducted similar tests, and obtained additional information between 2002 and 2006[8)], because their former results of the scaled overpressures tended to indicate not a little lower values than Kingery’s ones.

4. Numerical analysis model

In the numerical model, the detonation wave propagation process of TNT was not taken into account, and highly pressurized and condensed air with the equivalent internal energy to 1 kg TNT is assumed to exist as initial condition, because the charge volume can be regarded as a point source compared with the whole analytical system. The product gas of TNT was presumed to have the same specific heat (1.4 [-]) as air, since only a single material can be used in the FCT scheme as mentioned before.

Dobratz et al. published the handbooks of HE’s properties in 1972 and 1981[9)]. The energy values of TNT in the handbooks are different, i.e. 6.0 and 7.0 $\mathrm{GJ\cdot m^{-3}}$, hereafter, these two models will be referred to as ‘TNT’ and ‘TNT2’, respectively. The values of specific heats in the handbooks are 1.35 and 1.30, respectively, but this difference has scarcely any effect on the present numerical results. Because the present numerical model uses only the specific heat of air in order to estimate the overpressure and the impulse in the air, as the numerical model by the FCT scheme cannot use two different material properties.

Figure 2 depicts the 3-D numerical analysis model. The

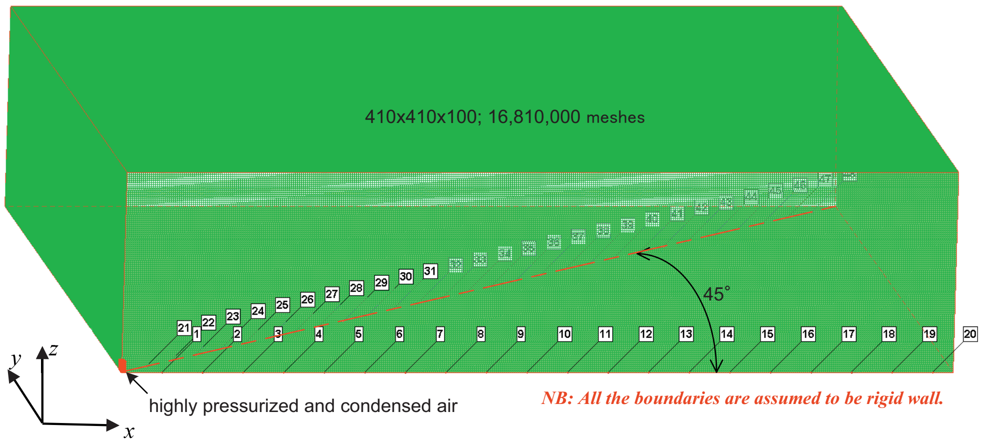

Figure 2 Numerical analysis model.

1/4 analysis system was adopted in consideration of its symmetrical property. The total numerical meshes are 16,810,000 (410 × 410 × 100) ; the whole analysis space was discretized uniformly by the cube, 5 mm on a side. All the boundaries were assumed to be rigid walls. The peak overpressure and impulse were measured every 1 m distant point from the explosion source in two directions : 0° and 45°, as shown in Figure 2. All the numbered history sensor points are located 2.5 mm high on the completely flat and rigid ground, i.e. at numerical meshes adjacent to the $z = 0$ plain.

5. Comparison between numerical simulations and experiments

5.1 Peak overpressure

Figure 3 indicates the comparison of peak overpressure vs scaled distance among the present numerical analyses, and Kingery's and MITI's (MITI : Ministry of International Trade and Industry ; METI after Jan., 2001 : Ministry of Economy, Trade and Industry) experimental results[3),8)]. Since there are no significant differences between Kingery '64 and '84 data, only the curve of '64 is plotted here. MITI 87 or Nakayama's 87 data[3)] estimate lower values than other data, especially between 5 and 10 $m·kg^{-1/3}$ by the scaled distance. The plotted date of METI 2002 or Nakayama's[8)] are close to Kingery's curve further more than MITI 87 curve. The data of TNT2 by the FCT indicate higher values than TNT all around, at the same time, the data of '0°' show considerably higher values than those of '45°'overall. It should be noted that the data of TNT2 [0°] are coincident with Kingery's curve. The notations of '0°' and '45°' mean that the sampling points are located on the lines from the explosion source at the angles of 0° and 45° with the x-axis, respectively as shown in Figure 2.

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5.2 Positive phase impulse

Figure 4 compares the relationship of positive phase impulse vs scaled distance among the present numerical analyses by FCT, Kingery 64 data, and two kinds of Nakayama's experimental results (MITI 87 and METI 2002). MITI 87 data estimate again much lower values than other data, especially between 2 and 20 $m·kg^{-1/3}$ by the scaled distance. The plotted data of METI 2002 are closer to Kingery's curve than MITI 87 curve, but still show lower values than Kingery's curve. The data of TNT 2 by the FCT indicate higher values than TNT all around, however, so much significant differences are not observed between the '0°' and '45°' data as compared to the peak overpressure results. The data of TNT2 [0°] and TNT2 [45°] are fairly coincident with METI 2002 data overall. These data are distributed in the intermediate area between the MITI 87 and Kingery 64 data. The TNT [45°]

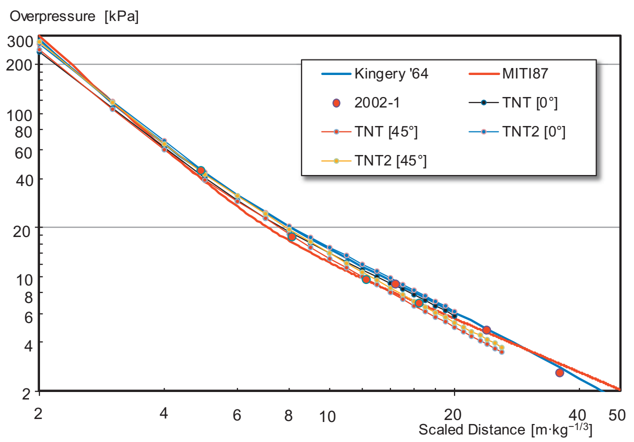

Figure 3 Comparison of peak overpressure vs scaled distance relations.

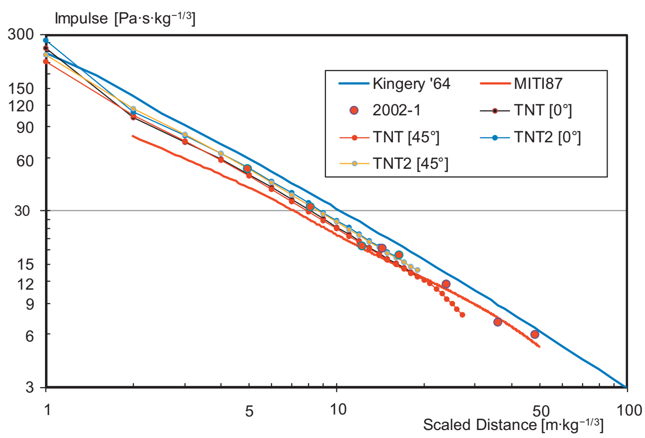

Figure 4 Comparison of positive phase impulse vs scaled distance relations.

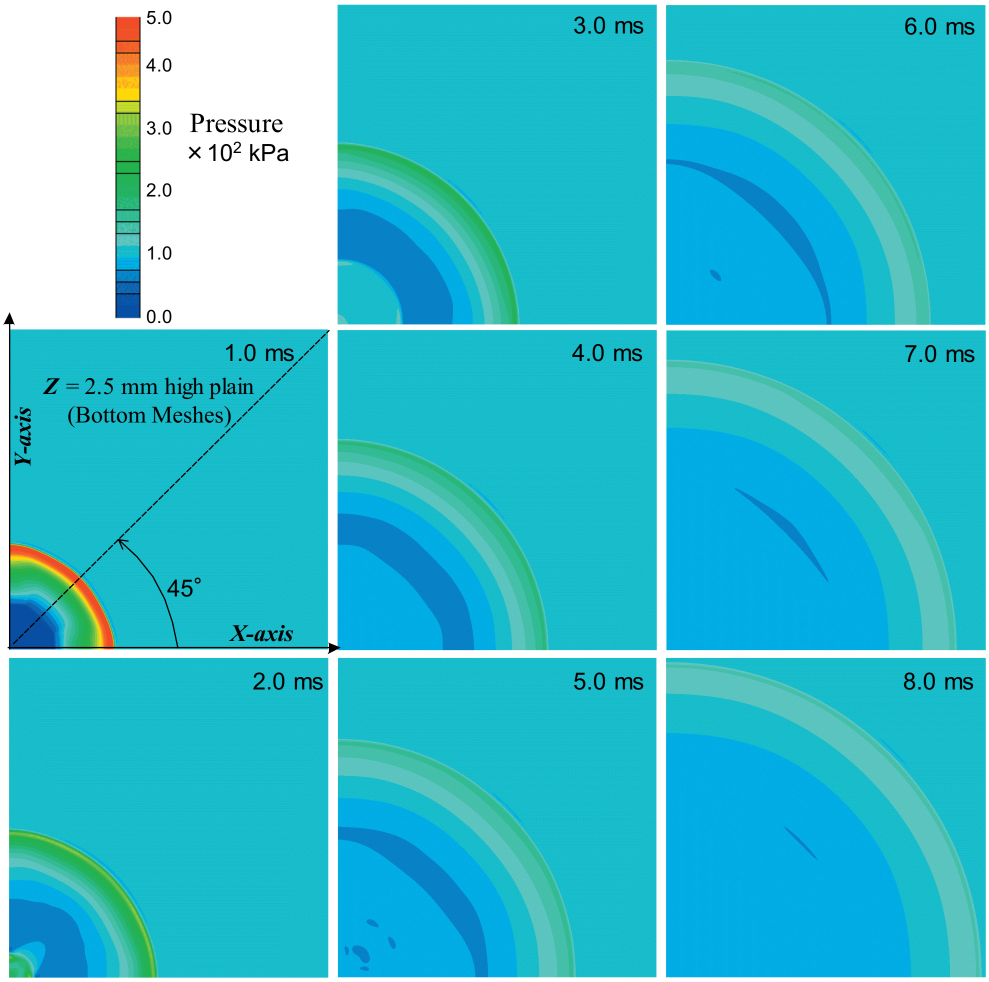

Figure 5 A time sequence of pressure contours on the rigid ground.

data show decreases outstandingly after the scaled distance of 20 m·kg$^{-1/3}$.

5.3 Pressure distribution on the ground

Figure 5 shows the numerical results on a time sequence at every one millisecond of pressure distributions on the ground assuming to be perfectly flat and rigid. This figure makes us to recognize that the points on the '45°' line are estimated to have lower pressures as shown in the section 5.1, although it is not a fact in the vicinity of the center of the explosion only at 2.0 ms.

6. Discussions

We summarize the present numerical analysis as follows :

i) In the case of peak overpressure, both TNT2 [0°] and TNT [0°] results by the FCT scheme are in fairly good agreement with Kingery 64 and METI 2002 experimental data up to the scaled distance of 20 m·kg$^{-1/3}$, although the TNT2 [45°] and TNT [45°]results indicate considerably lower values than these data, they are still higher than MITI 87 between 5 and 10 m·kg$^{-1/3}$ by the scaled distance.

ii) In the case of positive phase impulse, both TNT2 [0°] and TNT2 [45°] results approximately agree to METI 2002 experimental data up to the scaled distance of 20 m·kg$^{-1/3}$, although these data are lower than Kingery 84 and higher than MITI 87. Moreover, both TNT [0°] and TNT [45°] results show intermediate values between the TNT2's and MITI 87 data.

In the FCT scheme adopted by ANSYS AUTODYN there obviously exist some differences of the pressure estimations between the normal and diagonal directions to the advection cell faces, that is, the normal direction ('0°' or '90°') may estimate the most precise pressure compared with other directions, judging from the comparison with the experimental results. This is the fact for the pressure which is an intensive variable, but the impulse, which is an integrated variable of pressure by time, appears to be highly dependent upon the difference of internal energy, i. e. TNT (6.0 GJ·m^{-3}) and TNT2 (7.0 GJ·m^{-3}), which is an extensive variable.

On the basis of such knowledge obtained by the present numerical analysis, we shall suspect that the differences between Kingery's and MITI's experimental results might come from the following items :

a) The rigidity of the ground surface
b) The strength of TNT charge
c) The measuring or diagnostic system

The item a) is the most possible reason of the differences between MITI 87 and METI 2000s' results, because they were obtained through the experiments by using different test sites. However, it is impossible to explain all of the existing differences only by this reason. Other mechanisms seem to be involved with them, as only the numerical analysis results assume the perfectly rigid ground surfaces, but a numerical result does not always indicate the highest overpressure in Figure 3. Sometimes, the high-explosives produced in the U.S. have slightly higher densities, eventually higher detonation pressures than those in Japan, however it is difficult to come to such a conclusion affirmatively. As long as watching Figure 4, there seems not to exist any significant problems about pressure measuring systems, however only the impulses of Kingery '64 show considerably higher values than others. It is suggested that this fact might be brought by some problem about the evaluation method diagnosing the positive phase impulse : i.e. the definition of the "positive phase".

7. Concluding remarks

By using the FCT scheme of ANSYS AUTODYN, we clarified that pertinent peak overpressure and positive phase impulse can be estimated up to the scaled distance of 20 m·kg$^{-1/3}$. As depicted in Figure 2, we adopted the uniform mesh size of 50 mm to model the 1 kg TNT explosion on the rigid ground surface. The whole analytical system consists of 20.5 m to two horizontal directions, and 5.0 m to vertical direction ; that is, we modeled only the 1/4 region of the genuine whole system by taking into account the symmetrical property. The total numerical discretization was eventually achieved by using $410 \times 410 \times 100 = 16{,}810{,}000$ meshes.

The computer utilized in the present calculations is not so high-specific or special scientifically-prepared one, but an ordinary sort of personal computer. Actually, one of the authors purchased it for about 1,000. USD in the September of 2012 for the purpose of his office work ; the outline of the specification is : Intel Core i7 3.2 GHz, 12 GB RAM, 1TB HD, Windows 7 Professional for 64-bit with a 23" wide LED monitor. The CPU time required for the execution of one case is around two days by using such an ordinary PC, although various twists of the modeling have been given to save and reduce both the CPU time and main memory. From our experiential sense, it was not so easy to carry out such large-size calculations even by using leading parallel computer systems in the world ten years ago.

As a result, it is also suggested that the complicated 3-D fluid-structure interaction analyses will be possible to the scaled distance of 20 m·kg$^{-1/3}$ in the very near future.

Acknowledgement

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