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# Investigation of Trinitrotoluene (TNT) Equivalent Ratio of Spherical PE4 Charge Detonated on Non-Rigid Ground Surface Based on Peak Incident Overpressure Values

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***Abstract:*** ***Peak incident overpressure is a parameter which is commonly used to estimate explosive performance. However, the peak incident overpressure of an explosive differs from one another depending on various factors. Therefore, it is convenient to equate the overpressure of an explosive in question to the equivalent overpressure of a standard material such as trinitrotoluene (TNT). TNT equivalent ratio for a number of high explosives can be found in literature except for plastic explosive (PE4) which is often of limited references. In this paper, an investigation of TNT equivalent ratio of spherical PE4 charge detonated on non-rigid ground surface at standoff distances of 1 m to 3.1 m was carried out using numerical simulation software and validated with experimental results. Results showed that TNT equivalent ratio 1.37 appeared to be reasonably well for spherical PE4 charge detonations on non-rigid ground surface at a standoff distance of 1 m whereas 1.19 was appropriate for standoff distances of 2.6 m and 3.1 m. This indicates that TNT equivalent ratio based on peak incident overpressure varies with distance and therefore two values of TNT equivalent ratio are proposed in this case study.***

***Index Terms: TNT Equivalent Ratio, Peak Incident Overpressure, Plastic Explosive and AUTODYN3D,***

## I. INTRODUCTION

The detonation of high explosive is a rapid expansion of gas which poses very high pressure and temperature. As the gas expands, it will displace and compress the surrounding air. The air “shocks up” to produce a blast wave characterized by an instantaneous increase in pressure, as shown in Figure 1. The sharp “jump condition” is known as peak incident overpressure, $P_{so}$ and thereafter decreases exponentially to ambient pressure, $P_o$.

Evidently, two different sources of explosives with the same shape and mass will produce different values of peak incident overpressure, $P_{so}$. Therefore, it is convenient to equate the peak overpressure of explosive in question to the equivalent peak overpressure of a standard material such as trinitrotoluene (TNT) (Smith and Hetherington, 1994). The “TNT equivalent ratio” refers to the mass ratio of the explosive in question that will produced equal peak overpressure to that equivalent mass of TNT. The TNT equivalent ratio for a number of high explosives detonated under various conditions like free air, above and on ground surface are well documented in textbooks, journal articles and manuals (Kinney and Graham, 1985; Kingery and Bulmash, 1984) that are utilised for blast-resistant designs as well as characterising blast effects on structures. Formby and Wharton (1996) conducted an experiment to determine TNT equivalency ratio for several commercial explosives detonated on ground surface which includes Super Dopex, Penobel 2, Anobel and Special Gelatin 80. Later, Wharton et al. (2000) conducted an experiment to determine TNT equivalent ratio for other types of explosives which were detonated in free air condition (i.e. PE4, Penobel 2, Super Dopex, TNT, Nitroguanidine, Powergel 700 and Driftex). In 2004, Rigby and Sielicki conducted a numerical simulation and blast experiment to determine TNT equivalent ratio of hemispherical shape of PE4 charge detonated on rigid concrete slab. The TNT equivalent ratio of 1.2 was found to be the best to produce blast wave by the hemispherical PE4 detonations on rigid surface. There also appeared to be a range of equivalency ratios for PE4 landmine detonated underground, in which equivalency ratios with a range of 1.09 – 1.37 were suggested by Weckert and Anderson (2006). However, there appears to be no research that determines TNT equivalency ratio of spherical shape of PE4 charge detonated on non-rigid ground surface. Therefore, in this paper, an investigation of TNT equivalent ratio of spherical PE4 charge detonation on non-rigid ground was performed using AUTODYN3D and the results were then validated with an experiment previously conducted by the author (Jestin et al., 2016).

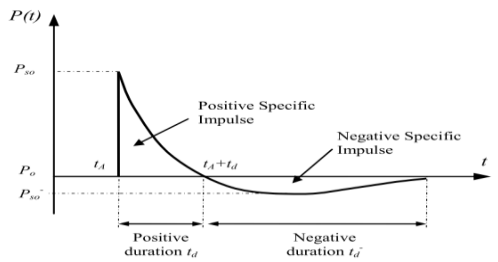


**Figure 1. Blast wave profile (Ngo et al. 2007)**

**Experimental Test Setup and Results**

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In the previous research, a series of blast experiments were carried out by the author at one of the military facilities in Malaysia (Jestin et al., 2016). Figure 2 shows a typical pressure-time history data recorded by pencil probe pressure sensors (PP1, PP2 and PP3) at standoff distances of 1, 2.6 and 3.1 meters respectively.

Numerical Simulation Model: The 2D and 3D Model Setup

Figure 3a and 3b show the AUTODYN2D and AUTODYN3D models respectively. The multi-material Euler solver was used to represent the air, ground and TNT. In Figure 3a, the expansion of gas from the detonation process (from $t$ = 0 until $t$ = $t_1$) is considered as an axisymmetric condition and therefore, the gas expansion was simulated in a 2D axisymmetric condition. In Figure 3b, the result of AUTODYN2D is mapped onto AUTODYN3D to fill the Eulerian domain, which corresponds to the *z*-axis, as an initial condition.

The AUTODYN2D domain has a dimension of 2000 mm *x* 1000 mm with a quadrilateral element size of 10 mm. The AUTODYN3D domain has a dimension of 4500 mm *x* 1000 mm *x* 2000 mm at *x*, *y*, *z* axes respectively with the size of uniform quadrilateral element of 50 mm. The model had been set to be symmetrical at *x*-*z*-plane and therefore, only a quarter of charge was simulated in order to reduce the computational time. The flow out boundary condition was applied at the 4 sides of the 3D domain to enable the air pressure to flow out. Pressure gauges (numbered as 1, 2 and 3 as shown in Figure 3b) were placed at the same location as the experiment to measure the peak incident overpressure.

Constitutive Models

***Properties of detonation***

The explosive detonation and expansion were modelled after Jones-Wilkins-Lee (JWL) equation of state (EOS) for TNT as shown in equation (1)

$$P = C_1\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + C_2\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where, $P$ is the hydrostatic pressure, whereas $C_1$, $C_2$, $R_1$, $R_2$ and $\omega$ are empirically derived constants which provide different constant values for different explosives; $V$ is the specific volume of detonation product over the specific volume of undetonated explosive and $E$ is specific internal energy. The value of $C_1$, $C_2$, $R_1$, $R_2$ and $\omega$ are 3.7377$x10^8$ MPa, 3.7471$x10^6$ MPa, 4.15, 0.9 and 0.35 respectively.

***Properties of air***

Air was modelled after Ideal Gas equation of state (EOS) as shown in equation (2)

$$P = (\gamma - 1)\,\rho E \quad (2)$$

where $P$ is the pressure, $\gamma$ is adiabatic constant which equals to 1.4, $\rho$ is the air density which equals to 1.225 kg/m$^3$ and $E$ is the specific air internal energy, 2.068$x10^5$ kJ/kg.

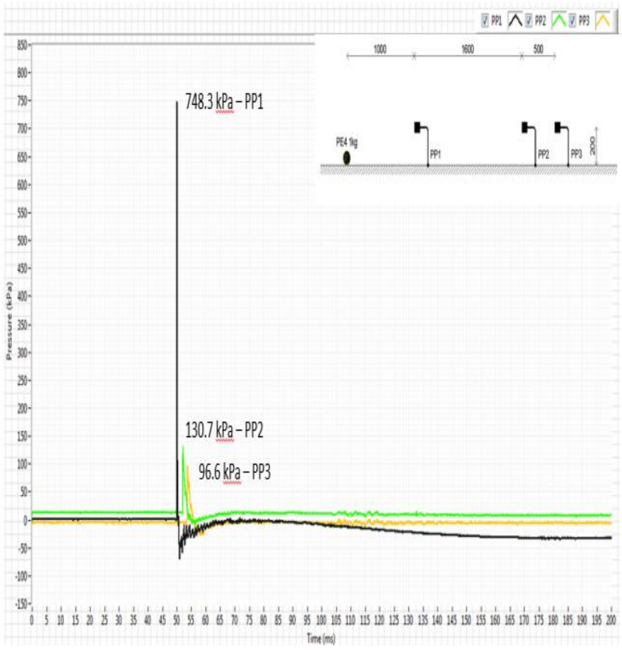


**Figure 2. The pressure-time history data recorded by pressure sensors (Jestin et al., 2016)**

***Properties of non-rigid ground (sand)***

The EOS of sand was described by plastic compaction curve from the polynomial function of pressure-density. The soil was considered a failure when the minimum pressure value, $P_{min}$ = -1$x10^{-3}$ Pa was reached (Laine and Sandvik, 2001).

Tested TNT Equivalent Ratio of Spherical PE4 Charge

In order to investigate the TNT equivalent ratio of spherical PE4 charge, the following situation was analysed (refer Table 1).

a. Case study number 1: The incident peak overpressure measurement from blast experiment for detonation of 1 kg PE4 at standoff distances of 1 m, 2.6 m and 3.1 m was used as a reference (Jestin et al., 2016).

b. Case study number 2: TNT equivalent ratio of 1.8 is suggested by Smith and Hetherington (1994) for surface burst condition. Due to the ground not an efficient reflector, 20% of the energy was lost producing crater and ground shock. The weight of TNT explosive was modelled as 1.8 kg. The incident overpressures were measured at the same standoff distances as the experiment.

c. Case study number 3: TNT equivalent ratio of 1.37 is suggested by ConWep for pressure equivalent. Therefore, the TNT mass was modelled as 1.37 kg. It should be noted that the equivalent ratio was based on air burst data (Hyde, 1991).

d. Case study number 4 : TNT equivalent ratio 1.19 is suggested by ConWep for pressure impulse equivalent which is derived from air burst data. Therefore, the TNT mass was modelled as 1.19 kg (Hyde, 1991)



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| Case study | Type of explosive | Standoff distance (m) | Charge or explosive mass (g) | Density ($kg/m^3$) | Radius (mm) | Tested TNT equivalent ratio of PE4 | Condition |
|---|---|---|---|---|---|---|---|
| 1 | PE4 | 1<br>2.6<br>3.1 | 1000 | 1601 | - | - | Experimental |
| 2 | TNT | 1<br>2.6<br>3.1 | 1200 | 1630 | 64.12 | 1.8 | Simulation |
| 3 | TNT | 1<br>2.6<br>3.1 | 1370 | 1630 | 58.54 | 1.37 | Simulation |
| 4 | TNT | 1<br>2.6<br>3.1 | 1185 | 1630 | 55.86 | 1.19 | Simulation |

## II. RESULTS

Figure 4 shows the compilation of peak incident overpressure measurement obtained from AUTODYN3D model for all TNT equivalent ratios tested at a standoff distance of 1 m. The figure clearly shows that TNT equivalent ratio has an influence on the magnitude of peak incident overpressure. The higher the ratio values, the higher the peak overpressure will be. This was expected due to TNT equivalent ratio being proportional to the radius and mass of explosive. Figure 5 shows the comparison of peak incident overpressure for all TNT equivalent ratios of PE4 tested both by numerical and experiment tests.

## III. DISCUSSION

The numerical simulation models had over predicted the experimental results as the standoff distance increases. The TNT equivalent ratio of 1.8 suggested by Smith and Hetherington (1994) showed the highest peak incident overpressure and over predicted amongst other ratios at all standoff distances with percentage differences of about 21% to 73%. This was expected as the actual experiment test was conducted on a non-rigid surface. The non-rigid ground surface had an influence on the incident overpressure measurement as blast energy imparted to the ground had been absorbed during crater formation and less energy was reflected. Therefore, the experimental results produced lower pressure as compared to numerical results which assumed a rigid ground. Meanwhile, the numerical simulation results of ratios 1.37 and 1.19 provided the lowest percentage difference at standoff distances of 1 m and 2.6 m to 3.1 m respectively. This indicates that TNT equivalent ratio based on peak incident overpressure varies with distance and therefore two values of TNT equivalent ratio are proposed in this case study. The differences are due to the dissimilarity of methods and procedures between the previous research and this study.

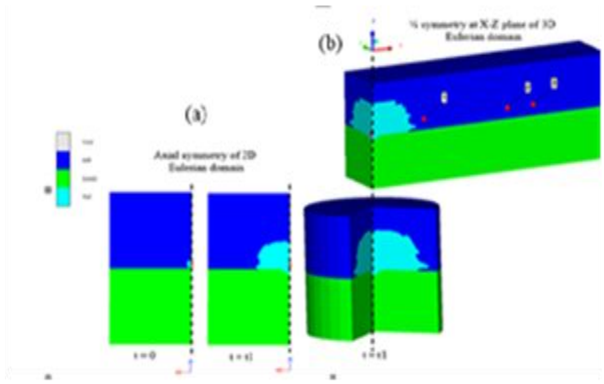


**Figure 3. (a) The AUTODYN2D model for mapping into AUTODYN 3D (b). The mapped file was then used to fill the AUTODYN3D domain as an initial condition.**

## IV. CONCLUSION

In this paper, an investigation of TNT equivalent ratio of spherical PE4 charge detonated on non-rigid ground surface at standoff distances of 1 m to 3.1 m was carried out using numerical simulation software AUTODYN3D. The results of numerical simulation analyses conducted for different TNT equivalent ratios found in literature were validated with experimental blast test conducted in previous research. It was found that TNT equivalent ratio of 1.37 appeared to be reasonably well for spherical PE4 charge detonations on non-rigid ground surface at a standoff distance of 1 m with a percentage difference of 1.5% to experimental results. Meanwhile, the TNT equivalent ratio of PE4 of 1.19 is in moderate agreement for both standoff distances of 2.6 m and 3.1 m. This indicates that TNT equivalent ratio based on peak incident overpressure varies with distance and therefore, two values are proposed in this case study.

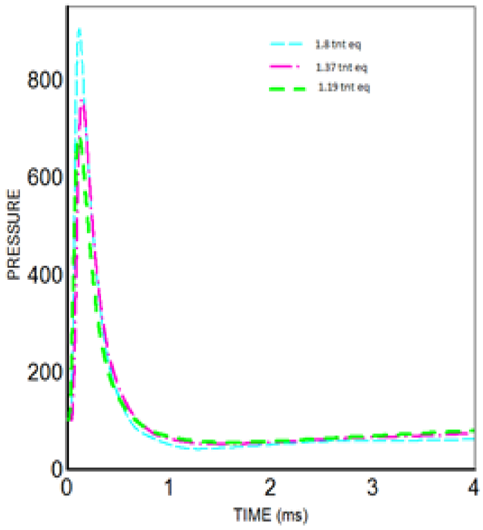


**Figure 4. Comparison of peak incident overpressure values from AUTODYN3D analysis for TNT equivalent ratio of PE4 at a standoff distance of 1 m**

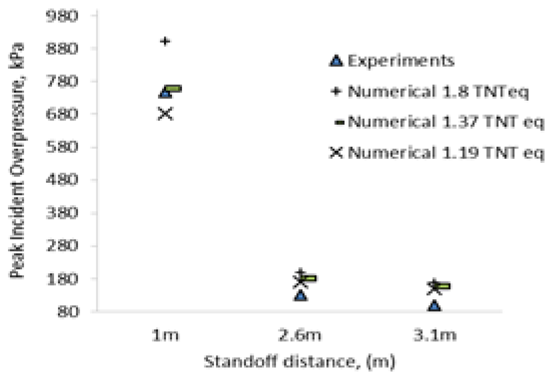


**Figure 5. Comparison of peak incident overpressure results from AUTODYN3D and experimental results for TNT equivalent ratio of PE4 at all standoff distances**

## V. ACKNOWLEDGMENTS

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