Article

A study of sympathetic detonation of 155 mm munitions from blast wave output

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This paper presents findings of an explosion risk evaluation study to obtain basic data concerning the sympathetic detonation of munitions for safe treatment of munitions. Trinitrotoluene (TNT) was used as a standard explosive and model munitions of 155 mm in diameter were exploded in the field experiment. The static overpressure of blast waves were measured by 6 piezoelectric gages located at between 10 m and 100 m. From the blast data, blast wave parameters (peak overpressure, time of arrival, duration and positive impulse) were obtained and TNT equivalent masses of munition(s) were estimated based on the peak static overpressure and positive impulse. Results showed that sympathetic detonation occurred up to 17 munitions. Moreover, the TNT equivalent mass increased with distance. This tendency may be due to the slow burning of TNT in the acceptor munitions.

1. Introduction

A number of experimental and numerical studies have been presented on the hazard assessment of sympathetic detonation of various munitions[1-2]. MIL-STD-2105B [3] has been established for the standard tests and test procedures for assessment of safety and insensitive munitions characteristics for munitions, munition subsystems and explosive devices. However, the hazard of sympathetic detonation during excavation of munitions and their explosion output has not been studied. To address this, a field experiment was conducted using 155 mm munitions filled with trinitrotoluene (TNT) to record blast wave pressures, fragment velocity and expansion behaviors of metal cases. This paper reports the results of blast pressures, evaluates TNT equivalent mass as an explosion output index and discusses the occurrence of sympathetic detonation. A description of the method and results of high-speed motion picture cameras are also presented [4].

2. Experiment setup

The sympathetic detonation test consists of detonating one munition (donor) adjacent to one or more like munitions (acceptors). The objective is to evaluate the likelihood of a detonation reaction being propagated from one unit to another within a group or stack of munitions. According to MIL-STD-2105B, one or more acceptors are positioned at location(s) deemed most vulnerable to sympathetic detonation. The donor is typically positioned at the center of the group or stack. Where appropriate, the test setup also incorporates dummy units to provide additional confinement of the donor and acceptor(s). In a departure from this procedure, the present study examines the sympathetic detonation test during excavation. In this case, the donor is positioned at the top of the group or stack and its confinement is only a shallow cover of earth mound.

Arrangements of test munitions for sympathetic detonation test are shown in Figure 1 and the explosives used are shown in Table 1; No.1-1-1is a

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Table 1 Experimental conditions

Experimental No.	TNT explosives			Booster explosives			Placement of explosive		
	Type	Mass (kg)	Size (mm)	Type	Mass (kg)	Size (mm)	Placement	Type	Distance (mm)
No. 1-1-1	Munition	6.8	O.D. 155	Picric acid	0.097		Horizontal	HOB*	350
No. 1-2-1	Munition	13.6	O.D. 155	Picric acid	0.097		Vertical	SOD**	50
No. 1-3-1	Munition	13.6	O.D. 155	Picric acid	0.097×2		Horizontal	HOB*	350
No. 1-3-2	Munition	20.4	O.D. 155	Picric acid	0.097		Vertical	SOD**	50
No. 1-4-1	Munition	122.4	O.D. 155	Picric acid	0.097		Horizontal	DOB***	500
No. 3-1	Explosive	10.03	φ202×204	Pentolite****	0.19835	φ51×61	Surface	HOB*	372
No. 3-2	Explosive	100.51	φ442×417	Pentolite****	2.03	φ125×105	Surface	HOB*	846

*; height of burst=height between the center of explosive and ground surface

**; stand off distance= distance between the bottom of munition and ground surface

***; depth of burst =depth between the center of explosive and ground surface

****; PETN:TNT = 50:50 by mass

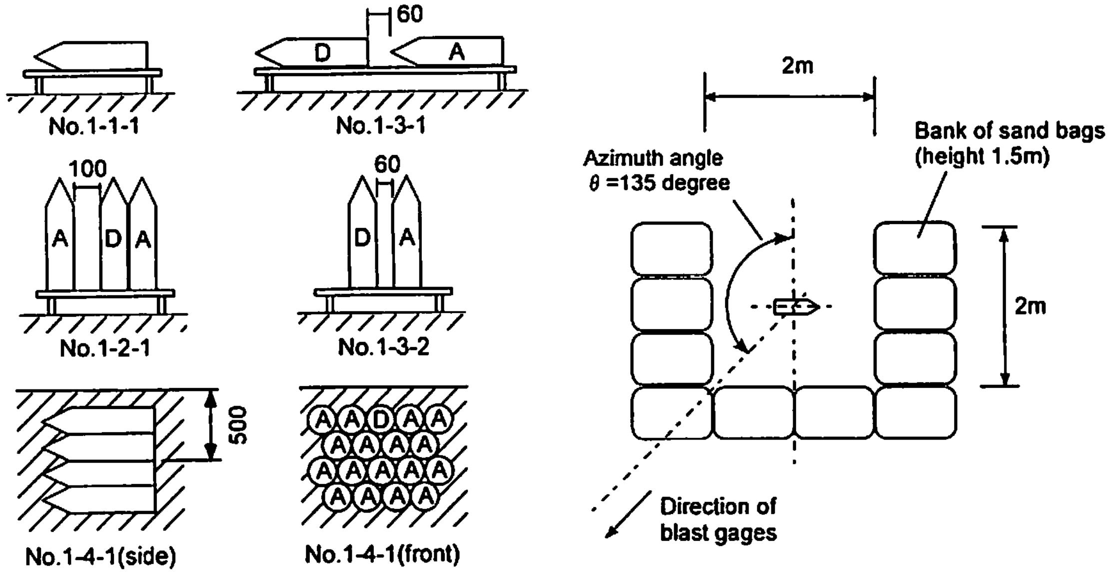

Fig. 1 Experimental conditions

test for detonation of a single munition; No.1-2-1 is for 1 donor and 2 acceptors positioned side-by-side (separation distance is 100 mm and 0 mm); No.1-3-1 is a test for 1 donor and 1 acceptor positioned tail-to-nose (ibid. 60 mm); No.1-3-2 is a test by 1 donor and 1 acceptor positioned side-by-side (ibid. 60 mm); No.1-4-1 is for 1 donor and 17 acceptors positioned side-by-side (ibid. 0 mm) buried shallow underground at the depth of explosion of 0.5 m. The munition size was about 630 mm in length and 155mm in diameter and the mass of explosive was 6.8 kg of TNT (ρ_0=1575 kg·m^{-3}) and its booster was 0.097 kg of picric acid (ρ_0=1420 kg·m^{-3}). For the calibration of pressure gages, surface burst of right cylindrical cast TNT explosives (ρ_0=1600 kg·m^{-3}) having a mass of 10 kg and 100 kg in test No. 3-1 and No. 3-2 and its boosters were 0.2 kg and 2 kg of pentolite (pentaerythritol tetranitrate (PETN):TNT=50:50 by mass)(ρ_0=1620 kg·m^{-3}), respectively were detonated (scaled height of burst was about 0.18 m·kg$^{-1/3}$) .

A bank made up of large sand bags was stacked around the munition to restrict fragment flight path to 1 direction as shown in Figure 1(b). The inner size of the bank was 2 m wide, 2 m deep and 1.5 m high. The angle between axi-symmetrical axes of the bank and direction of blast measurements (azimuth angle) was θ =135° , not 90° , as shown in Figure 1(b). The bank was not used for TNT explosions. The donor or pentolite booster was initiated using a 2 explosion-bridgewire (EBW) type detonators (RP501, RISI Co. Inc.) and double hold detonating cord of 6.5 m in length. The detonators were fired by initiation system FS43 (field experiment use, RISI Co. Inc.).

Air blast pressures were measured at the distances of 10.3 m and 16.5 m by PCB piezoelectric pressure gages HM102A12 (sensitivity=3.6μ V·Pa⁻¹, linearity=1% full scale, resonant frequency>500 kHz) and 26.4 m, 40.4 m, 60 m, and 100.9 m by PCB piezoelectric pressure gages HM102A07(14.5μ V·Pa⁻¹, 1% full scale, >250 kHz). Each pressure gage was flush-mounted to a sharp-edged stainless steel disk (which had a diameter of 90 mm) in the direction where the peak static overpressure would be measured. The pressure gages were located ≈1 m above ground.

Output from the pressure gages were recorded by the digitizer (Gage 14100, 8 ch., 10 MSample/sec., 16 bits/ch.) located at 120 m from the explosion point. The observation rooms were located at 180 m from the explosion point. The trigger pulses for EBW detonators and the digitizer were supplied from a digital delay pulse generator (BNC 555, Berkely Nucleonics Co. Ltd.). The experiments were conducted at the test site of Ojojihara of the Japan Defense Agency in Miyagi prefecture.

4. Results

4.1 Static overpressure time records

The time records of blast waves at distance of 16.5 m for No. 1-1-1, 1-2-1, 1-3-1, 1-3-2, 1-4-1 are shown in Figure 2. The blast wave history of No. 1-4-1 looks similar to the ideal blast waveform of TNT. On the other hand, the blast wave histories of No. 1-1-1, 1-2-1, 1-3-1, and 1-3-2 differed from the ideal case. They contain more than 2 peaks as a pulse train, and the primary peak is lower than the second peak. The reason for this may due to the reflection of blast waves on the inner wall of the bank. The bank of sand bags were completely broken out in No.1-4-1, but in the other experiments the banks were only partially broken.

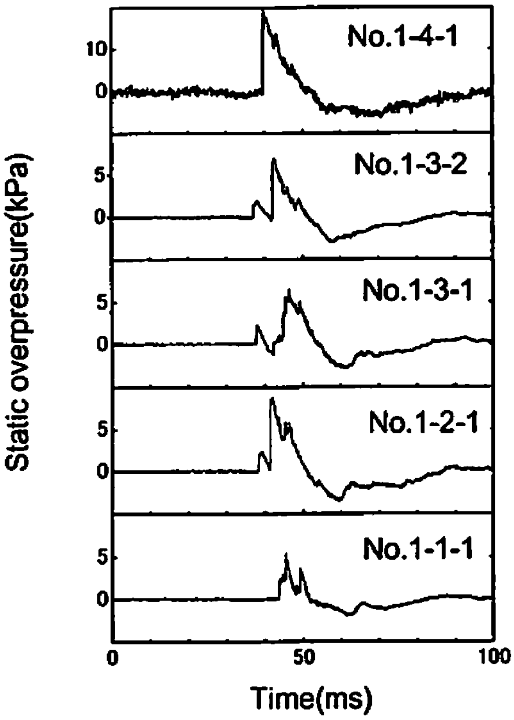

Fig. 2 Blast wave histories at distance of 16.5 m.

The figure clearly shows that the peak pressures from the multi-munitions cases are higher than that of single munition. This suggests that some acceptor(s) reacted and contributed to generate the blast wave. The details are discussed later in terms of TNT equivalent mass.

4.2 The blast data for TNT as a function of scaled distance

The time-histories were interpolated by smooth cubic natural spline functions to obtain 4 characteristic blast parameters: peak static overpressure; time-of-arrival; duration of positive phase, and the positive impulse (the time-integral of the overpressure during the positive pressure phase). Peak static over pressure and scaled impulse as a function of scaled distance are shown

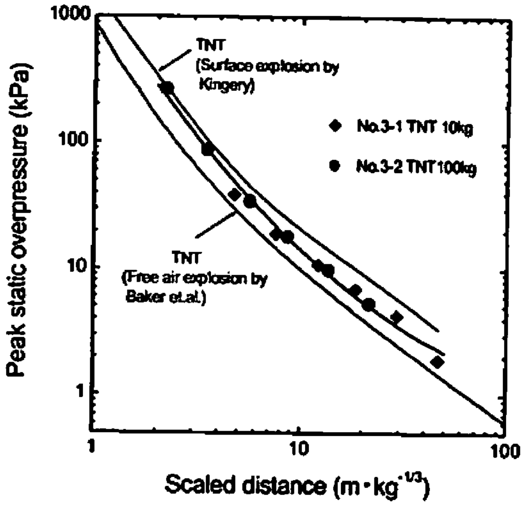

Fig. 3 Peak static overpressure as a function of scaled distance for TNT

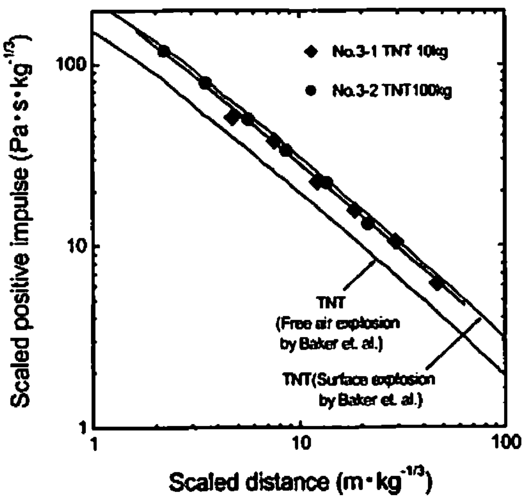

Fig. 4 Scaled positive impulse as a function of scaled distance for TNT

in Figures 3-4. Also shown in Figure 3 are results for TNT of the surface burst by Kingery [5] and for TNT in free air which were presented by Baker et al. in graphical forms [6].

The impulse data for TNT of the surface burst in Figure 4 is estimated from data for TNT in free air by Baker et al. by assuming that the impulse from free air explosion of 2 kg of TNT is equivalent to that from surface explosion of 1 kg of TNT (an assumption of mirror reflection of blast waves on rigid wall). The peak static overpressures were lower than that of the surface burst but higher than that of the free air explosion, which is likely due to the effect of the height-of-burst (HOB) of TNT. The present data show good agreement with the previous results [7] where the scaled HOB was the same value of about 0.18 m·kg$^{-1/3}$. This confirms the validity of the blast wave measurement system so the results for TNT blast wave data will be used to obtain the TNT equivalent mass of the munition(s).

4.3 The blast data for munition(s) as a function of distance

Among blast parameters for the munitions, peak static over pressure and positive impulse as a function of distance are shown in Figures 5-6. From the results it was found that the more the number of munitions, the higher the blast effect; the order of magnitude is No.1-4-1>No.1-2-1>No.1-3-1 ≒ No.1-3-2> No.1-1-1. This tendency was partially

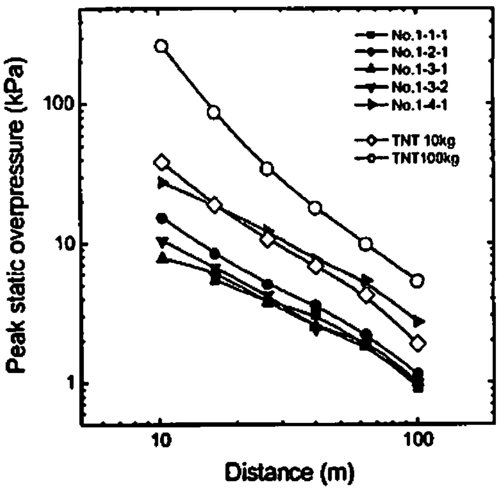

Fig. 5 Peak static overpressure as a function of distance for munition(s)

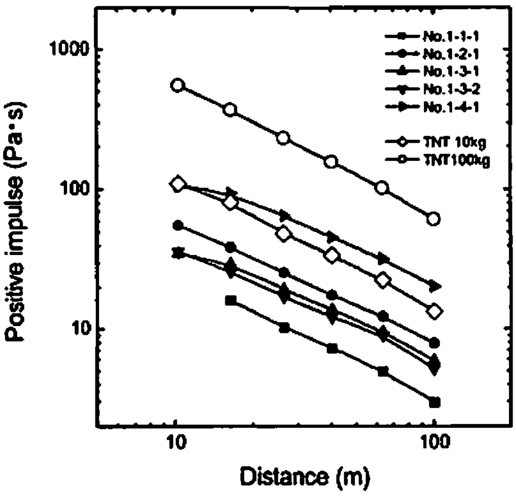

Fig. 6 Positive impulse as a function of distance for munition(s)

recognizable in peak static overpressure data and clearly recognizable in positive impulse data.

4.4 TNT equivalent mass for munitions

TNT equivalent masses for munition(s) were estimated based on peak static overpressure and positive impulse. Peak static over pressure and scaled impulse for TNT 10 kg and 100 kg were fitted by a polynomial function of scaled distance. TNT equivalent mass based on peak static overpressure (M_P) is obtained simply by the following equation.

$$M_P = \left(\frac{R}{\bar{R}_{TNT}}\right)^3 \qquad (1)$$

where, R = distance(m), and $\bar{R}_{\mathrm{TNT}}$ is the scaled distance for TNT at the scaled distance that the peak static overpressure for TNT gives the same value for munition(s) at distance . For TNT equivalent mass based on positive impulse (M_I), the values were scaled by cube root of the mass. The values should be obtained by an iterative method.

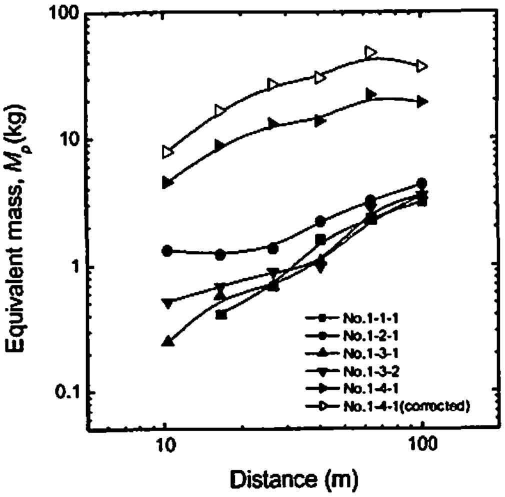

Fig. 7 TNT equivalent mass based on peak static overpressure as a function of distance

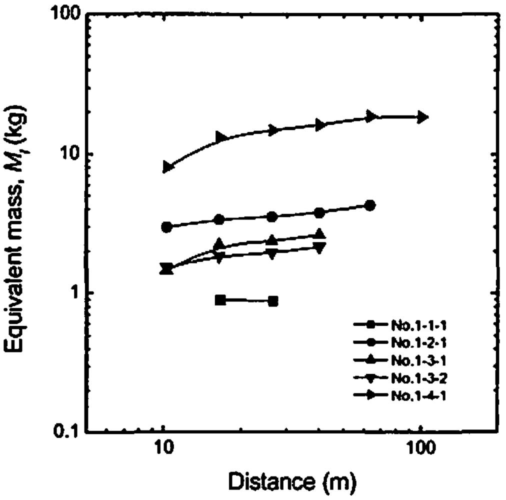

Fig. 8 TNT equivalent mass based on positive impulse as a function of distance

TNT equivalent mass based on peak static overpressure and positive impulse as a function of distance are shown in Figures 7-8, respectively.

Figure 7 gives two results for No.1-4-1; one is from original data, and the other is from corrected values of underground explosion to surface explosion. For the correction, NSWC data were used [8]; the ratio $R_p=P_s/P_u$ was defined as a correction factor to surface explosion, where P_u is peak static overpressure at a depth of burst of 0.5 m, and P_s is peak static overpressure at a depth of burst of 0 m. For six distances, R_p = 1.36±0.36. TNT equivalent masses were obtained from the peak static overpressure multiplied by the correction factor; the results are shown in the figure by open symbols. For positive impulse, no correction was applied since there was no available data.

5. Discussion

5.1 Detonation of single munition

Considering the single munition detonation (No.1-1-1) first, TNT equivalent mass M_P was ~0.4 kg at the near distance and increased about one order of magnitude against distance, and was ~3 kg at the far distance. The values M_I could be estimated only at shorter distances, and they were about 1 kg. Blast pressures for munition data are reported to be about half the explosive data at an azimuth angle of θ =0° from the result of blast pressures for underground magazine explosion [9]. This may be explained by the energy loss mechanism by the kinetic energy of metal case. Peak overpressure at an azimuth angle of θ =135° is reported to be greatly attenuated against data at θ =0° for an explosion in a cylindrical metal pipe [10]. In the present experiments, the bank was made of large sand bags not steel and its tunnel length was not so long, so the attenuation effect may be lower. Due to these facts, the TNT equivalent mass for single munition was considered low. Therefore, it is preferable to think that the TNT mass of the present experiment should be discussed in terms of relative values and absolute values should be used as reference data.

5.2 Sympathetic detonation for two or three munitions

If acceptor(s) reacted and generated energy that contributed to blast waves, TNT equivalent mass would be larger than that of a single munition. Figure 1 clearly shows that the peak overpressures for multiple munitions are higher than for a single munition. The relation between the number of munitions and M_P at the far distance is not clear, but M_P at the near distance is proportional to the number of munitions. M_I is clearly proportional to the number of munitions: M_I for No.1-1-1is about 1 kg, 3~4 kg for No.1-2-1, about 2 kg for No.1-3-1 and No.1-3-2. All the acceptors may have reacted and generated blast waves independent of the arrangement and separation distances of the munitions. According to MIL-STD-2105B, munition reactions are ranked (Type V) burning, (Type IV) deflagration or propulsion, (Type III) explosion, (Type II) partial detonation, and (Type I) detonation in terms of increasing hazard severity. M_I increased gradually against distance, and blast output was high at the far distance, the reaction type of the acceptor may be an explosion reaction (Type III) or partial detonation reaction (Type II). This conclusion is supported by the fragment sizes of the metal case and the state of destruction of the witness plates placed around the munitions.

5.3 Sympathetic detonation for 18 munitions

In this case, both M_P and M_I increased against distance. M_P and M_I were around 10 kg at the near distances but increased to ~20 kg at the far distance and the corrected M_P for surface explosion was ~80 kg. Therefore, all the 17 acceptors reacted and generated blast waves from the comparison of M_I for single munition with that of the 18 munitions case. This conclusion is supported by the fragment sizes of the metal case and the state of destruction of the witness plates placed around the munitions, just as in the fewer munitions case. Moreover, the increase of TNT equivalent mass at the far distance suggests that the burning of TNT was much slower than the detonation reaction in the acceptors. These findings confirm that there is a high risk of sympathetic detonation in the present experimental conditions.

6. Conclusions

In order to evaluate the explosion risk of munitions at excavation, sympathetic detonation tests of 1, 2, 3 and 18 TNT filled 155 mm munition(s) were conducted and the resultant blast waves were measured by pressure gages, and their blast parameters were obtained. The TNT equivalent mass based on both peak static overpressure and positive impulse were evaluated and the occurrences of sympathetic detonation were discussed. Here are the main results.

TNT equivalent mass based on peak overpressure increased with distance and that based on positive impulse was almost constant in the single munition case. The TNT equivalent mass based on impulse for a single munition was ~1 kg and was much smaller than the mass of TNT in the munition (7kg). The underestimation of TNT equivalent mass in the present study is probably due to the diffraction of blast waves by the bank surrounding the munition(s). Therefore, the TNT equivalent mass in the present study should be evaluated relatively and it is preferable to consider that the absolute values as reference data.

For the sympathetic detonation test of 2 or 3 munitions of surface burst, and 18 munitions of shallow underground burst, the TNT equivalent mass increased rapidly for peak static overpressure base and gradually for positive impulse base. TNT equivalent masses based on positive impulse were almost proportional to the number of munitions and it may be concluded that all of the acceptors reacted sympathetically independent of the arrangement and separation distance of the munitions. Moreover, TNT equivalent mass increased with distance, TNT in the acceptor may burn relatively slowly compared with first reaction of detonation.

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