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# Damage Effects of Explosion of Shelled Explosive in Concrete

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**ABSTRACT**

The damage of concrete subjected to explosion loading is an important issue in defence engineering. The degree of damage to concrete is related to many factors, such as type of explosive charge, depth of burial, and parameters of concrete. In this study, three factors have been considered for experiments of shelled explosives in concrete targets, which are filling coefficient, length-to-diameter ratio, and depth of burial. The filling coefficient is from 0.1 to 1.0 by changing thickness of shell, and the length-to-diameter ratio is from 2.5. The unconfined compressive strength of concrete targets for test is 35 MPa. The experimental results showed that sizes of craters of concretes were varied depending upon the filling coefficient, the length-to-diameter ratio, and the depth of burial. The optimal values of filling coefficient, length-to-diameter ratio, and depth of burial of shelled charges have been obtained to get maximal damage regions of concrete targets. This study has provided a base for evaluating damage of concrete and designing penetrating warhead.

**Keywords:** Shelled explosive, concrete, filling coefficient, length-to-diameter ratio, depth of burial, crater, explosive leading, damage effect, protective engineering blast loading

## 1. INTRODUCTION

Concrete has been widely used as construction material for military and civilian applications. The response of concrete shelters subjected to blast loading is an important topic in protective engineering. The resistance of concrete against blast loading has been of great interest, not only to the designers of defence structures, but also to the developers of weapon systems. Tests of crater formation are probably appropriate tools to study the behaviour and destructive power of shelled charges and the response of concrete. The mechanism of crater formation is complex and is related to the dynamic physical properties of concrete, filling coefficient, and length-to-diameter ratio of shelled charges. Damage of concrete and rocks under blast loading were studied by some researchers[1-5]. Recently, Luccioni[6] proved the accuracy of numerical simulation of crater produced by underground explosions, and numerical analysis of crater formation due to underground explosions was done. Ohkubo[7] conducted explosion tests to examine failure modes of concrete plates subjected to contact explosion, and existing formulae have been applied to estimate these failure modes taken in the tests. Liu[8] used LS-DYNA code to numerically simulate explosion in concrete and soil, and the damage regions of concrete at different thicknesses of soil and depths of burial were procured.

## 2. EXPERIMENTAL SETUP

The aim was to investigate the damage effects caused by explosion of different charges in concrete targets. The degree of damage of concrete is related to many factors, such as type of explosive charge, depth of burial, and parameters of concrete. Therefore, three factors, filling coefficient, length-to-diameter ratio (L/D) (L-the charge length, D-the charge diameter) and depth of burial, were considered for the experiments.

### 2.1 Concrete Targets

The density of concrete target was 2280 kg/m$^3$, the compressive strength was 35MPa (cube strength at 28 days). The concrete was made of cement, sand, gravel and water. The mass proportion of cement, sand, gravel and water is 1: 1.37: 2.78: 0.46. The dimensions of each concrete target were 1200 × 1200 × 1200 mm$^3$. The concrete targets were buried underground, while top surfaces were on a horizontal plane. To remove the boundary effects, the wood plates of 20 mm thickness were filled between each target, and the concrete of 20 cm width were cast between the fringe targets and soil, as shown in Fig.1. The pre-drilled cavity located in the centre of each target was matched with its explosive charge.

### 2.2 Explosive Charges

The shell of charge was Chinese No.45 steel with density of 7850 kg/m$^3$. The tensile strength and yield strength of the steel were 600 MPa and 355 MPa, respectively. The shells were hollow cylinders, in which there were the cast explosive of Composition B. The Composition B was constituted by TNT and RDX, with mass of 40 per cent

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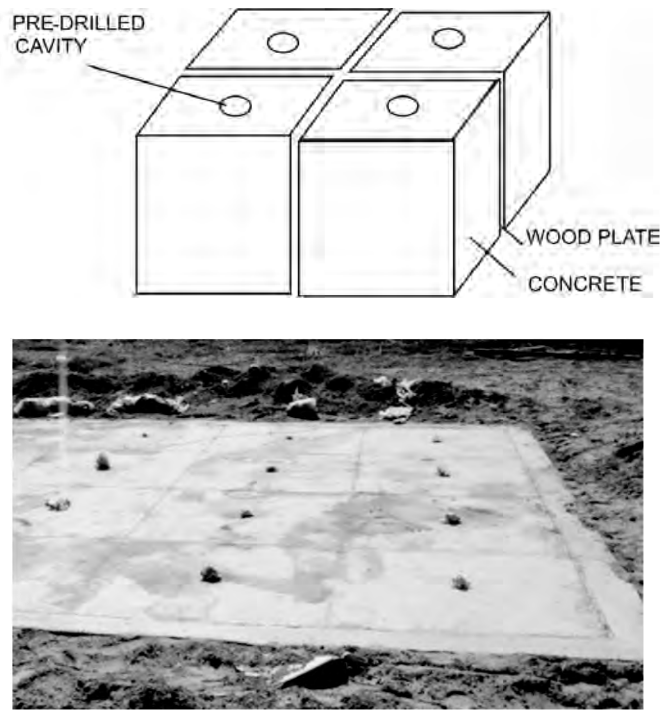


Figure 1. Concrete targets.

and 60 per cent. The density of Composition B was 1610 kg/m$^3$, and detonation wave speed was 7800 m/s, and detonation pressure was 24.5 GPa.

According to the filling coefficient and the ratio of length-to-diameter for experiments, 12 types of shelled charges were designed as shown in Table 1. The filling coefficient (FC) is defined as the ratio of the weight of the explosive to the total weight of shelled charge, which can be changed by the thickness of shells. In this study, the filling coefficient was varied from 0.113 to 1.0. The ratio of length-to-diameter was altered by the dimensions of explosive, which was from 2.5 to 10.0. The depth of burial (DOB) is defined as the distance from charge centre to the top surface of the concrete target. The experimental setup is shown in Fig. 2.

Table 1. Types of shelled charges

| Experiment No. | Dimensions of explosives (mm) | The ratio of length-to-diameter | Shell thickness (mm) | Quantity |
|---|---|---|---|---|
| 1 | Φ30 mm × 75 mm | 2.5 | 0 | 1 |
| 2 | Φ30 mm × 75 mm | 2.5 | 2 | 2 |
| 3 | Φ30 mm × 75 mm | 2.5 | 3 | 2 |
| 4 | Φ30 mm × 75 mm | 2.5 | 4 | 2 |
| 5 | Φ30 mm × 75 mm | 2.5 | 5 | 2 |
| 6 | Φ30 mm × 75 mm | 2.5 | 6 | 2 |
| 7 | Φ30 mm × 75 mm | 2.5 | 7 | 2 |
| 8 | Φ30 mm × 75 mm | 2.5 | 8 | 2 |
| 9 | Φ32 mm × 80 mm | 2.5 | 3 | 1 |
| 10 | Φ28 mm × 103 mm | 3.68 | 3 | 1 |
| 11 | Φ24 mm × 140 mm | 5.83 | 3 | 1 |
| 12 | Φ20 mm × 200 mm | 10.0 | 3 | 10 |

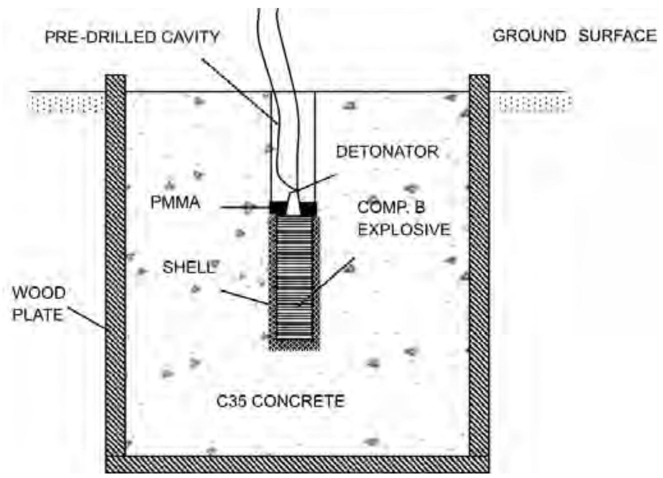


Figure 2. Experimental setup.

## 3. METHODOLOGY

Three groups of field tests were conducted. After igniting the charges, photographs were taken, and the crater depth and diameter were measured. The experiments met the goals of researching the effects of charges' shells, length-to-diameter ratio, and depth of burial on the craters of concrete targets. To accurately measure the crater volume, concrete debris was gently sweep away from the craters, and then the crater volume was filled by dry sand, and its cubage was measured by a cup with scale.

## 4. RESULTS AND DISCUSSION

### 4.1 Effects of the Filling Coefficient

In these experiments, the dimensions of explosives were diameter of 30 mm and length of 75 mm. The thickness of shells varied from 0 mm to 8 mm, that is, the filling coefficients were varied from 0.113 to 1.0, as shown in Table 2 and the depth of burialwas kept the same as 260 mm. The explosive was Composition B with weight of 85 g.

Fifteen explosive charges were detonated. Photograph depicting the damage patterns of some concrete targets after the tests are shown in Fig. 3. The craters were cone-shaped, with diameter varied in each crater. The details of conical craters have been listed in Table 2.

Results show that the radius of conical crater is more than the depth of conical crater, and the depth of conical crater is less than depth of burial. The concrete with crater has no large crack and neighbouring targets were perfect, which means the wood plates can dispel the boundary effects. So these targets can be regarded as semi-boundless due to no boundary reflected.

Figure 4 shows the crater volume versus shell thickness, the maximal conical crater volume is caused by the charge with 2 mm shell. The volumes of craters caused by the charges with 2 mm and 3 mm thick shells were both larger than non-shelled charges. However, the volumes of craters produced by charges with 4 mm--8 mm shells were less

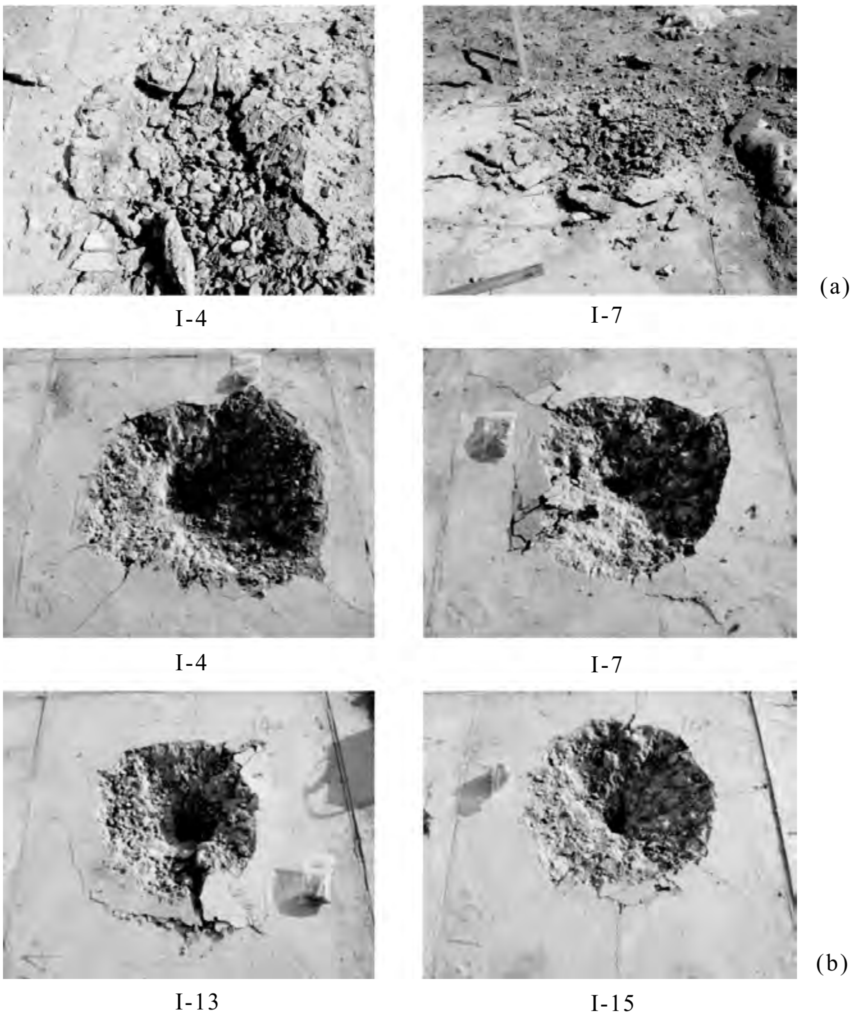


**Figure 3. Photographs of damage region of some concrete targets: (a) before removing detritus, (b) after removing detritus.**

**Table 2. Details of experiments and craters**

| Experiment Number | Shell thickness (mm) | Filling coefficient | Conical crater volume ($mm^3$) | Conical crater dia (mm) | Conical crater depth (mm) | Visible radial cracks |
|---|---|---|---|---|---|---|
| I-1 | 0 | 1.000 | $24.85 \times 10^6$ | 790~820 | 124 | 11 cracks with 1~3 |
| I-2 | 2 | 0.391 | $35 \times 10^6$ | 870~1000 | 157 | 8 cracks with 5~6 |
| I-3 | 2 | 0.391 | $33.95 \times 10^6$ | 800~900 | 200 | 6 cracks with 4~7 |
| I-4 | 3 | 0.291 | $32.2 \times 10^6$ | 720~900 | 200 | 8 cracks with 3~5 |
| I-5* | 3 | 0.291 | - | - | - | - |
| I-6 | 4 | 0.228 | $18.2 \times 10^6$ | 710~760 | 170 | 9 cracks with 1~2 |
| I-7 | 4 | 0.228 | $18.55 \times 10^6$ | 670~720 | 140 | 11 cracks |
| I-8 | 5 | 0.186 | $14.7 \times 10^6$ | 620~660 | 152 | 7 cracks with 1~3 |
| I-9 | 5 | 0.186 | $16.1 \times 10^6$ | 670~720 | 135 | 6 cracks with 1~2 |
| I-10 | 6 | 0.155 | $14.7 \times 10^6$ | 680~730 | 135 | 6 cracks with 1~2 |
| I-11 | 6 | 0.155 | $17.5 \times 10^6$ | 720~850 | 185 | 6 cracks with 2~3 |
| I-12 | 7 | 0.131 | $18.2 \times 10^6$ | 740 | 150 | 5 cracks with 2~10 |
| I-13 | 7 | 0.131 | $12.95 \times 10^6$ | 610~650 | 115 | 4 cracks with 1~2 |
| I-14 | 8 | 0.113 | $16.8 \times 10^6$ | 700~740 | 140 | 10 cracks with 1~3 |
| I-15 | 8 | 0.113 | $17.15 \times 10^6$ | 710~720 | 125 | 8 cracks with 1~4 |

Note: * The explosive of shelled charge deflagrated in this experiment.

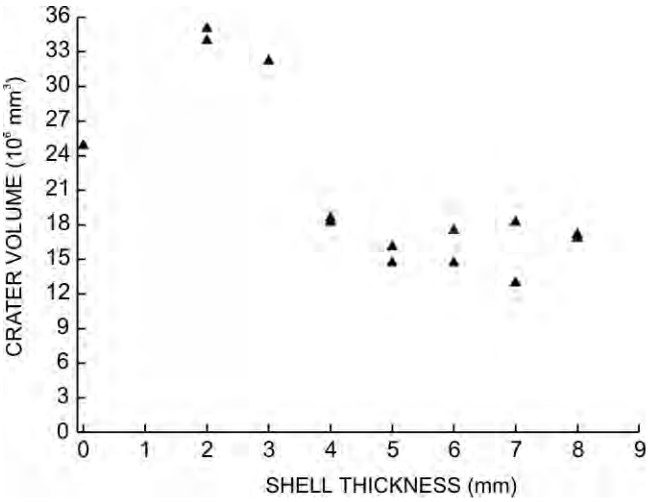


**Figure 4. Conical crater volume versus shell thickness.**

than non-shelled charges. It shows that the and proper thickness shell is propitious to concrete damage.

According to detonation theory of explosive and stress waves in solid, the following equation can be formed[9]:

$$p = \frac{\rho_0 D^2}{\gamma + 1} \cdot \frac{2\rho_m C_p}{\rho_m C_p + \rho_0 D} \tag{1}$$

where $p$ is pressure (in $Pa$) of the interface between explosive and concrete or steel shell; $\rho_0$ and $D$ are density (in kg/m$^3$) and detonation wave speed (in m/s) of the explosive, respectively; $\rho_m$ and $C_p$ are density (in kg/m$^3$) and sound wave speed (in m/s) of concrete or steel shell, respectively; $\gamma$ is the polytropic gas constant.

The pressure of the interface between explosive and concrete after explosive detonation was 21GPa, and that of the interface between explosive and steel shell was 37 GPa. So the steel shell can increase the pressure of shock wave, which enlarges the volumes of craters of concrete, i.e., the thickness of shells were 2 mm and 3 mm. When the thickness of shell is more, the energy for fragmentation of shell is more. When the energy for cracking the concrete is less, the volumes of craters decrease. The proper thickness of shell of the explosive charge increase the damage region of concrete.

However, the other case, that accurate insertion of an unshelled charge into a cavity made in a concrete block without leaving any air gap is difficult should not be ignored. To reduce the effect of air gap, the soil was filled into the gap. The soil may ultimately reduce the crater volume too, which may lead to the result that the crater volume produced by non-shelled charge is lesser than that produced by the charge with 2 mm thickness shell.

### 4.2 Effects of Length-to-diameter Ratio

In this group, four experiments for effects of length-to-diameter ratio were performed. The length-to-diameter ratio was varied from 2.5 to 10.0 by altering dimensions of explosive charges, as shown in Table 3. The explosive was composition B with weight of 102 g, and the thickness of shell was 3 mm. Depth of burials of these four experiments were 242 mm. From Table 3, the conical crater volume under length-to-diameter ratio D = 3.68 was the largest, and the volume under length-to-diameter ratio = 10.0 was the smallest, which indicate the length-to-diameter ratio is one of the important factors of shelled charges for damaging concrete targets.

When explosive charges exploded in concrete targets, the damage effects of concrete were determined by stress waves and detonation products. Compressive stress waves generated internally could damage the concrete, and made concrete strength reduce. The tensile waves reflected from free surface of concrete caused concrete surface to spall and made cracks in concrete to expand. Moreover, the cracks growth was accelerated and broken concrete was thrown out by detonation products. Therefore, the crater was formed due to stress waves and detonation products.

The distribution of stress waves and detonation products was different, when explosive charges with different length-to-diameter ratios exploded in concrete. The area, that shock wave caused by explosion directly applied to the concrete, increased with increasing length-to-diameter ratio, but the energy density of detonation products decreased with increasing length-to-diameter ratio. Therefore, there exists an optimal length-to-diameter ratio for the same weight of explosive charge to bring the maximal crater volume.

### 4.2 Effects of Depth of Burial

Ten experiments in this group were conducted, in which the number of III-6 and II-4 was one and the same experiment. The weight of composition B was the same as 102 g, and the thickness of shell was 3 mm. Other parameters have been list in Table 4. Results from Table 4 and Fig. 5 show that conical crater volume changes tardily when depth of burial was <190 mm. However, the depth of burial significantly affects the parameters of crater

**Table 3. Parameters of experiments of length-to-diameter ratio**

| Experiment Number | Dimensions of explosives (mm) | Length-to –diameter ratio | Weight of explosive (g) | Shell thickness (mm) | Conical crater volume (mm$^3$) | Conical crater diameter (mm) | Conical crater depth (mm) |
|---|---|---|---|---|---|---|---|
| II-1 | Φ32mm × 80mm | 2.5 | 102.0 | 3 | $36.90 \times 10^6$ | 740~830 | 220 |
| II-2 | Φ28mm × 103mm | 3.68 | 102.0 | 3 | $50.40 \times 10^6$ | 860~990 | 234 |
| II-3 | Φ24mm × 140mm | 5.83 | 102.0 | 3 | $34.30 \times 10^6$ | 710~800 | 214 |
| II-4 | Φ20mm × 200mm | 10.0 | 102.0 | 3 | $21.70 \times 10^6$ | 700~790 | 160 |

**Table 4. Parameters of experiments of depth of burial**

| Experiment Number | Dimensions of explosives | Depth of burial (mm) | Conical crater volume (mm$^3$) | Conical crater diameter (mm) | Conical crater depth (mm) |
|---|---|---|---|---|---|
| III-1 | Φ20 mm × 200 mm | 120 | 13.30 × 10$^6$ | 580~630 | 135 |
| III-2 | Φ20 mm × 200 mm | 147 | 11.55 × 10$^6$ | 570~650 | 119 |
| III-3 | Φ20 mm × 200 mm | 160 | 11.55 × 10$^6$ | 570~610 | 140 |
| III-4 | Φ20 mm × 200 mm | 190 | 11.20 × 10$^6$ | 560~590 | 139 |
| III-5 | Φ20 mm × 200 mm | 225 | 17.15 × 10$^6$ | 650~780 | 154 |
| III-6 | Φ20 mm × 200 mm | 242 | 21.70 × 10$^6$ | 700~790 | 160 |
| III-7 | Φ20 mm × 200 mm | 265 | 28.70 × 10$^6$ | 800~910 | 245 |
| III-8 | Φ20 mm × 200 mm | 275 | 37.10 × 10$^6$ | 800~810 | 195 |
| III-9 | Φ20 mm × 200 mm | 300 | 33.23 × 10$^6$ | 690~760 | 245 |
| III-10 | Φ20 mm × 200 mm | 330 | 22.40 × 10$^6$ | 620~800 | 150 |

when depth of burial is >190 mm, and there are two steeper slopes in Fig. 5 with depth of burial increasing.

In Fig. 5, the volumes of craters are small and almost the same, when depth of burial is < 190 mm. The reason being considerable portion of explosion energy was dissipated into the air to form shock waves, and the energy exerting on the concrete was reduced. With the depth of burial increasing, the energy dissipation in air decreased, and the energy acting on the concrete to form crater increased, so the volumes of craters were increased.

When the depth of burial was 275 mm, the maximal crater volume was obtained from this group of experiments. Therefore, depth of burial of 275 mm in this group of experiments may be optimal depth of burial, which produces the maximal conical crater. In this case, the energy efficiency of explosive on concrete is maximal. However, when depth of burial is greater than the optimal depth of burial and continues to increase, the explosion energy to form conical crater decreases and more and more explosion energy absorbed in concrete under the crater, so the crater volume decreases gradually. On the other hand, with the depth of burial increasing, the strength of reflected tensile waves

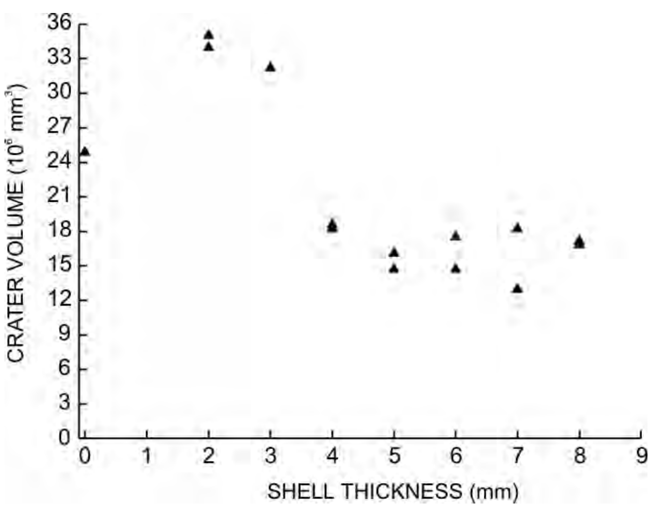


**Figure 5. Conical crater volume versus depth of burial.**

from the free surface of concrete was decreased, which reduced tensile damage of concrete, and gradually reduced the crater volume.

## 5. CONCLUSIONS

In this study, three groups of field tests were conducted to investigate damage effects of shelled charges explosion in concrete targets. Three main factors, the filling coefficient, length-to-diameter ratio, and the depth of burial were considered and to get different damage effects. Photographs of damage concrete structures show that wood plates implanted between concrete targets get reduced the boundary effects. The damage region of concrete caused by the charge with filling coefficient of 0.391 is maximal in the experiments for filling coefficient effects. The damage region of concrete was decreased with length-to-diameter ratio increasing from 3.68 to 10.0. Experimental results show that there are optimal values of filling coefficient, length-to-diameter ratio, and depth of burial to get the maximal damage region.

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