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Rear-surface collapse perforation of concrete targets under buried explosion

Zhuo-Ping Duan [a], Hai-Ying Zhang [a,b], Zhong-Jie Lu [a,*], Zhuo-Cheng Ou [a], Yan Liu [a], Feng-Lei Huang [a]

[a] State Key Laboratory of Explosive Science and Technology, Beijing Institute of Technology, 100081 Beijing, PR China
[b] China Nuclear Power Engineering Co., Ltd., 100840 Beijing, PR China

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ABSTRACT

Experimental research on collapse and perforation failure at the rear surface of a concrete target induced by buried explosion of a cylindrical explosive charge was performed. The aim is to develop an available approach to predict the critical collapse thickness under explosion loading. It is found that both the diameter and the length-to-diameter ratio of the cylindrical explosive charges have remarkable influence on the critical collapse thickness. Based on the experimental data for the plain concrete with the compressive strength of 35 MPa, an analytical expression for the relation between the dimensionless critical collapse thickness on concrete target and the length-to-diameter ratio of explosive charge is developed via dimensional analysis. Moreover, it is also found that there exists an incomplete similarity of the critical collapse thickness in the diameter of explosive charge, although the complete similarity in the length-to-diameter ratio alone cannot be established.

1. Introduction

Concrete is widely used in protection works against the impact loadings resulted by missile penetration and explosion. As is well known, associated with the penetration of a missile into a concrete wall and then explosion inside, a compressive stress wave is formed and propagates across the concrete wall. At the rear free surface of the concrete wall, the compressive wave reflects as a tensile wave, which will result in spalling and collapse of the wall under certain conditions. The fragments with high kinetic energy caused by the spalling and collapse can endanger both the personal and the facilities in the protection works, which makes it of great significance to understand well the collapse failure occurred at the rear free surface of protection works.

Over the past decades, much work has been opened on the failure behaviors of concrete targets under blast loadings. For example, Xu and Lu [1,2], Zhou et al. [3], Wu et al.[4], Tai et al. [5], Yi et al. [6] studied the dynamic behaviors of thin concrete slabs under shock wave loadings resulted from external explosion. In general, comparing to the dimension of the charge, the distance between the charge and the concrete target is large enough, and then the target is supposed to point and the concrete is a single-degree-of-freedom (SDOF) system [7–10]. Rabczuk et al. [11–15] carried out an effective work on the meshfree method, and the simulation precision is improved constantly. They simulated the damage process of concrete targets under contact explosion using the meshfree method, and compared to the cracks of experiment results. Ohtsu et al. [16], Yuan et al. [17] and Wang et al. [18], were mainly focused on the blast-induced spalling at the rear surface of a concrete target under contact explosion on the front surface of the concrete target. Fu et al. [19] and Wu et al. [20] investigated the shallow buried explosion inside a semi-infinite concrete body, and Fu et al. presented a minimum value of the blast crater index and the relation between the dimension of blast crater and the amount of explosive charge. In general, the so-called spherical explosive charge assumption was used in most of previous literature, even for cylindrical one, and thus the influence of the geometrical properties of cylindrical explosive charges on material failure was neglected. Recently, however, Liu et al. [21] carried out a series of tests on the shallow buried explosion in semi-infinite concrete targets and measured the volume of blast crater. They found that the length-to-diameter ratio of explosive charges have important effects on the blast crater and obtained an optimal length-to-diameter ratio to get the maximal damage regions on the front surface of concrete targets. Therefore, the spherical explosive charge assumption should not be available for cylindrical charges with a large length-to-diameter ratio, especially for modern weapons in which the maximum length-to-diameter ratio of explosive charges can reach high up to 10 or more. It is then necessary to incorporate the length-to-diameter ratio into analysis in order to obtain a more realistic estimation on spalling and collapse perforation of concrete walls. Moreover, the influence of the length-to-diameter ratio on the collapse crater or collapse perforation at the rear surface is

* Corresponding author. Tel.: +86 10 6891 3127.
E-mail address: lvzhongjie@bit.edu.cn (Z.-J. Lu).

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much different from the blast crater at the front surface. However, to the best of the authors' knowledge, so far, the collapse crater at the rear surface of a concrete target under buried explosion is far from complete, and, especially, less experimental work has addressed such a problem.

In this paper, the collapse perforation at the rear surface of a concrete target under buried explosion was investigated experimentally, with both the diameter and the length-to-diameter ratio of the cylindrical explosive charge taken into account. The relationship between the dimensionless critical collapse thickness of the concrete target and the critical length-to-diameter ratio of the explosive charge is developed via the dimensional analysis, which implies also that the assumption of spherical explosive charge is not always available for such a problem.

2. Experimental set-up

The density and uniaxial compressive strength of concrete material used in this study are 2.5×10^3 kg/m^3 and 35 MPa, respectively, which are measured after standard curing of 28-day. Considering the geometry of explosive charges, the dimension of the concrete targets are taken to be 1000 × 1000 × 700 mm, 1000 × 1000 × 800 mm, 1500 × 1500 × 700 mm, and 1500 × 1500 × 900 mm, respectively. For convenience, as is shown in Fig. 1, all of the concrete targets are casted into a monolithic one on concrete ground, in which some wood plates are inserted to block off each target as well as prevent possible crack growth across the boundary between any two neighbor targets. Moreover, to reduce the lateral boundary effect, subsidiary concrete layers of 300 mm in thickness are casted around the whole concrete structure. At the center of each concrete target, there is a pre-drilled charge hole with its diameter matched with that of the cylindrical TNT charges but much less than the dimension of the concrete target.

The casted cylindrical TNT explosive charges with the density of $\rho_e = 1.58 \times 10^3$ kg/m^3 and four different diameters of 20, 25, 30 and 40 mm, respectively, were used in the experiments. The amount of explosive charge is then determined by the diameter and the length of the explosive charges. An electrical detonator is fixed at one end of explosive charge, as shown in Fig. 2, and the positive initial detonation is adopted.

Fig. 3 is a side elevation drawing for the TNT charge in a concrete target. It is known that the depth of the collapse crater R at the rear surface of the concrete target will increase with amount of the explosive charge, as shown in Fig. 4. When the depth of collapse crater R is just equal to the residual thickness of concrete target R_c, a critical collapse state is reached. Thus, the critical collapse thickness R_c can be defined as the critical value of R, and, correspondingly, the amount of explosive at the critical state is termed as the critical amount of explosive charge M_c. In this experimental study, the so-called up-and-down method is adopted and the amount of explosive charges is regulated with the minimum increment of 10 g. To avoid the influence of accumulate damage on the experimental data, a new target is used in each single shot. In addition, the pre-drilled charge holes are not stemmed for simulating better the actual buried explosion inside the concrete shields under attack of modern weapons.

Fig. 2. TNT charge.

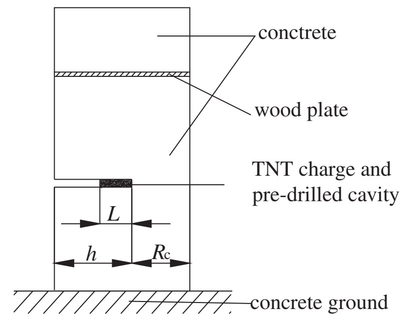

Fig. 3. TNT charge in a concrete target.

3. Results and analysis

The tests were carried out in four groups, corresponding to four different diameters of the cylindrical TNT charges, and 3–6 different residual thicknesses were taken in each group. A series of tests are performed to find the critical collapse thickness for different diameters and different length-to-diameter ratios of the cylindrical TNT charges.

The postmortem observation on typical targets are presented as shown in Fig. 5a–d, in which the diameter of pre-drilled hole/cylindrical TNT charge is 30 mm and the residual thickness is 250 mm (h = 450 mm). Four tests are performed on four concrete targets, corresponding to the amount of explosive charges of 50, 80, 100, 110 g, respectively. It can be seen that there is only a great number of crack on the rear surface of concrete targets when the amount of explosive charges are 50 g and 80 g. For other two tests, the depths of the collapse craters are 140 and 310 mm, respectively. In other words, there is $R_{100} < R_c < R_{110}$ (the numerical subscripts denote the amount of explosive charges), and thus M_c = 105 g is taken as the critical amount of explosive charge in this case for the minimum increment of explosive charge of 10 g. In this way, totally, fifty tests were completed on fifty concrete targets, each concrete target is used only once, and eighteen different conditions of explosive charges were obtained, as listed in Table 1.

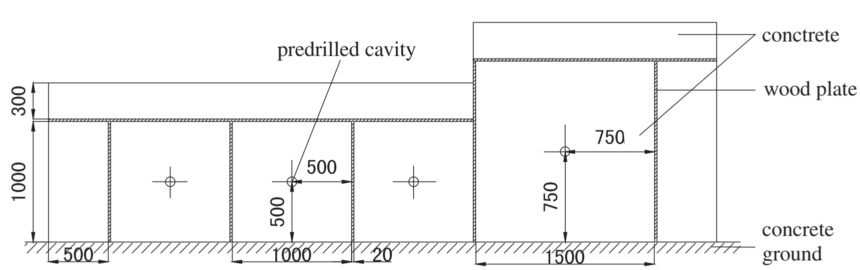

Fig. 1. Concrete targets.