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Rear-Surface Collapse of Finite Thickness Concrete Targets under Internal Explosion

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ABSTRACT

An experimental investigation on the buried internal explosion in finite thickness concrete targets was carried out, with the aim at developing an available criterion for the critical collapse of rear-surface to determine the critical collapse thickness and the critical amount of explosive charge under different depth of buried. It is found, under a certain density and diameter of explosive charge, the critical collapse thickness increases monotonically with the length-to-diameter ratio or the amount of the explosive charge, but the increasing becomes slower down after the length-to-diameter ratio of the explosive charge is larger than about 5, which implies that the geometry of the explosive charge can have much influence on the damage and failure of concrete targets due to different mechanism of energy dissipation. Moreover, by using the dimensional analysis approach, the function relation between the dimensionless critical collapse thickness and the length-to-diameter ratio was obtained, which shows that the dimensionless critical collapse thickness depends on both the amount and the length-to-diameter ratio of the charge.

Keywords: Internal explosion, critical collapse thickness, damage and failure, spalling, concrete target, length-to-diameter ratio

1. INTRODUCTION

Concrete is one of widely used structural material in the civil and military protective engineering. It is associated with the penetration of a missile into and its explosion inside a concrete target, a compressive stress wave is formed and propagates to the rear free surface. When the compressive wave arrived at the rear free surface, a reflected tensile wave comes subsequently into being, which can result in spalling and collapse of the rear free surface under certain critical conditions. The failure fragments with high kinetic energy can endanger considerably the equipment as well as the people inside the protective structure, which makes it of great significance to understand in depth such a rear-surface spalling and collapse phenomena of a finite thickness concrete target under internal explosions and gets more attentions in the realm of protection of the structures.

Over the past decades, much work has been done on the damage and failure of concrete targets under explosion and impact loadings. Fu[1], *et al.*, Wang[2], *et al.*, and Wu[3], *et al.* investigated the shallow buried explosion in semi-infinite concrete bodies, and the relationship between the geometrical properties of blasting crater and the amount of spherical explosive charge was determined; Xu[4], *et al.*, Zhou[5,6], *et al.*, Lu[7], *et al.*, Tai[8], *et al.*, Wang[9], *et al.*, and Yi[10], *et al.* studied the dynamic response of concrete thin slabs subjected to the shock wave loadings generated by explosions in air. Rabczuk and Eibl[11], Ohtsu[12], *et al.*, and Yuan[13], *et al.* concerned mainly with the blast-induced spalling damage at the rear free surface of concrete thin slabs under contact explosion on the front surface of targets. It is worthy of special mention that a spherical explosive charge assumption, even for a cylindrical one, was always made for such a problem in most of previous literature, by which the influence of the geometrical properties of the explosive charge on the material damage and failure are neglected. Liu[14], *et al.* has pointed out experimentally, the length-to-diameter ratio of a cylindrical explosive charge has much effect on the damage and failure of concrete targets. Therefore, in the authors' opinion, the spherical explosive charge assumption should not be available for the charge in a large length-to-diameter ratio, especially for modern weapons, in which the maximum length-to-diameter ratio of explosive charge can reach high up to 10. However, so far, the rear-surface damage and failure of a finite thickness concrete target under internal explosion is not yet very well understood, and especially less experimental work has addressed such a problem.

In this paper, the rear-surface collapse of a finite thickness concrete target under internal explosions is investigated experimentally, and the geometrical property of explosive charge is taken into account. The amount of explosive charge at the critical collapse state is obtained, and then the relationship between the critical collapse thickness and the critical amount of a cylindrical explosive charge is proposed by using the dimensional analysis approach. The results can serve as a reference for damage analysis of the deep earth-penetrating weapons and the design of deeply buried protective structures.

2. EXPERIMENTAL SET-UP

The concrete used in the study has a uniaxial compressive strength of 35 MPa measured after standard curing of 28-day and the density of 2.5×10^3 kg/m^3. The dimension of each concrete target is 1000 mm × 1000 mm × 700 mm or 1500 mm × 1500 mm × 900 mm. For convenience, as is shown in Fig. 1, several targets are casted into a monolithic one, in which some wood plates are inserted to block off each target as well as to prevent possible

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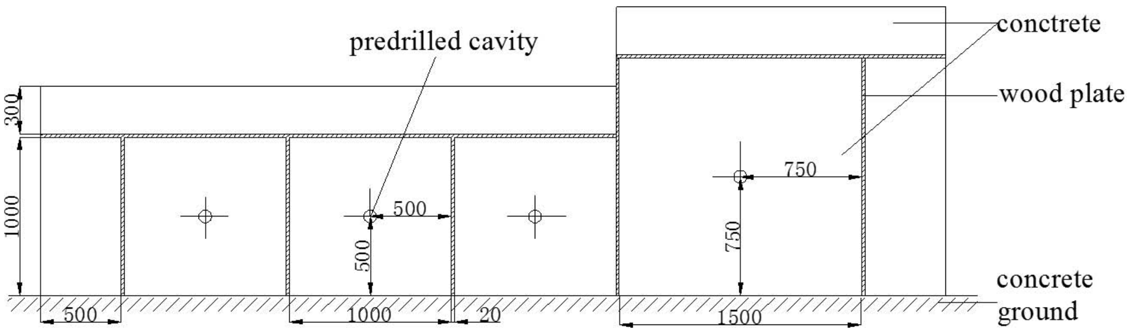


Figure 1. Concrete targets.

crack growth across the boundary between two neighbour targets. To avoid the lateral boundary effect, subsidiary concrete layers of 500 mm in thickness are casted around the monolithic target. A pre-drilled charge hole with its diameter less than one thirtieth of the minimum dimension of the target is located at the center of each of the target. Totally, eight kinds of the charge hole in different depth are pre-drilled for eight different depths of burial of 350 mm, 370 mm, 400 mm, 450 mm, 490 mm, 500 mm, 520 mm, and 525 mm, respectively.

The casted cylindrical TNT explosive charge is used in all the experiments, with its diameter D = 30 mm and density ρ_e = 1.58×10^3 kg/m^3, respectively. The charge amount is then determined by the length of the explosive charge. An electrical detonator is fixed at one end of the explosive charge, as shown in Fig. 2, and the positive initiation is adopted.

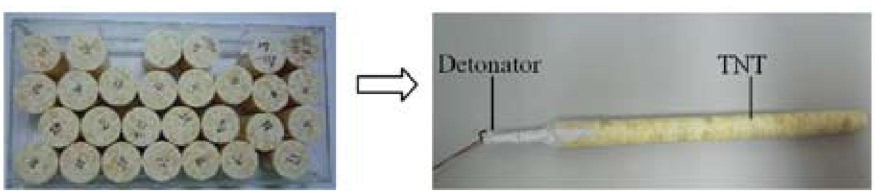


Figure 2. TNT charge.

It is easy to understand, for an internal explosion under a certain depth of burial, that the rear scab thickness or the depth of the blasting crater increases with the amount of explosive charge, and hence a critical collapse state can be defined as that when the depth of the blasting crater R equals to the residual length of the finite target R_c, as shown in Fig. 3. On the other hand, the residual length R_c can also be taken as a critical collapse thickness for an internal explosion with a given depth of burial, and the corresponding amount of explosive charge M_c can be defined naturally as the critical amount of explosive charge. In the experiments, for a given depth of burial and thus a fixed R_c, the critical collapse state can be acquired through increasing step-by-step the amount of explosive charge, and the critical amount of explosive charge can thus be determined as that at the critical collapse state. Moreover, the charged pre-drilled hole is not plugged up for simulating better the internal explosion of the modern weapons.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Twenty-six concrete targets are used in the experimental study, and twenty-four tests are completed. Experimental data are listed in Table 1, together with the qualitative descriptions of the rear-surface failure of the concrete targets.

A postmortem observation on typical targets of 700 mm in thickness and the critical collapse thickness of 250 mm is presented as shown in Figs. 4(a)-4(d), corresponding to the amount of explosive charge 50 g, 80 g, 100 g, and 110 g. There are no blasting craters in the first two tests, and the depth of the blasting crater for the last two tests is 140 mm, and 310 mm, respectively. In other words, there is $R_{100} < R_c < R_{110}$ (the numerical subscripts denote the amount of explosive charge), and thus M_c = 105 g is taken as the critical amount of explosive charge considered the minimum increment of explosive charge of 10 g in the experiment. The critical collapse states corresponding to eight different depths of burial can be determined, as listed in Table 2.

From the experimental results, the influence of the length-to-diameter ratio on the rear-surface collapse can be estimated. To describe quantitatively the relationship between the critical collapse thickness and the length-to-diameter ratio, the dimensional analysis approach is taken. For such an internal explosion issue, the governing parameters can be divided into two classes that describe explosive charge and concrete, respectively, which are listed in Table 3.

Taken the critical collapse thickness R_c as the quantity being determined, we have

$$R_c = f\left(\rho_e, \gamma, L, D, h; \rho_c, \sigma_t, \sigma_c, E, \mu\right) \quad (1)$$

It is easy to verify the parameters ρ_e, D and E as

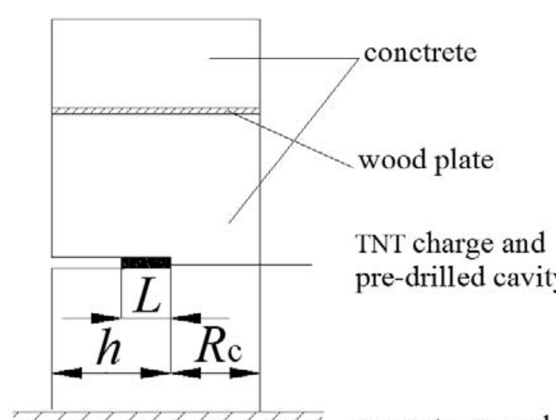


Figure 3. TNT charge in a concrete target.

Table 1. Experimental data of concrete targets

h(*mm*)	*M*(*g*)	*L*(*mm*)	*R*(*mm*)	R_c(*mm*)	Notes
520	30	26.70	-	180	No collapse crater
	60	53.50	180		Critical state
	80	71.50	180		-
490	90	79.60	250	210	-
	100	88.64	230		Collapsed seriously
450	50	44.62	-	250	No collapse crater
	80	71.50	-		No collapse crater
	100	89.18	140		-
	110	97.76	310		-
400	120	106.68	230	300	Collapse crater
	130	115.20	310		-
	150	133.80	320		Collapsed seriously
370	100	89.40	-	330	No collapse crater
	120	106.56	-		No collapse crater
	140	128.80	340		-
350	140	124.70	-	350	No collapse crater
	160	142.00	-		No collapse crater
	180	161.00	-		Collapsed seriously
525	190	171.00	-	375	No collapse crater
	220	196.00	190		Collapse crater
	250	223.00	370		-
500	250	222.00	-	400	No collapse crater
	300	262.00	230		Collapse crater
	330	292.00	470		Collapsed seriously

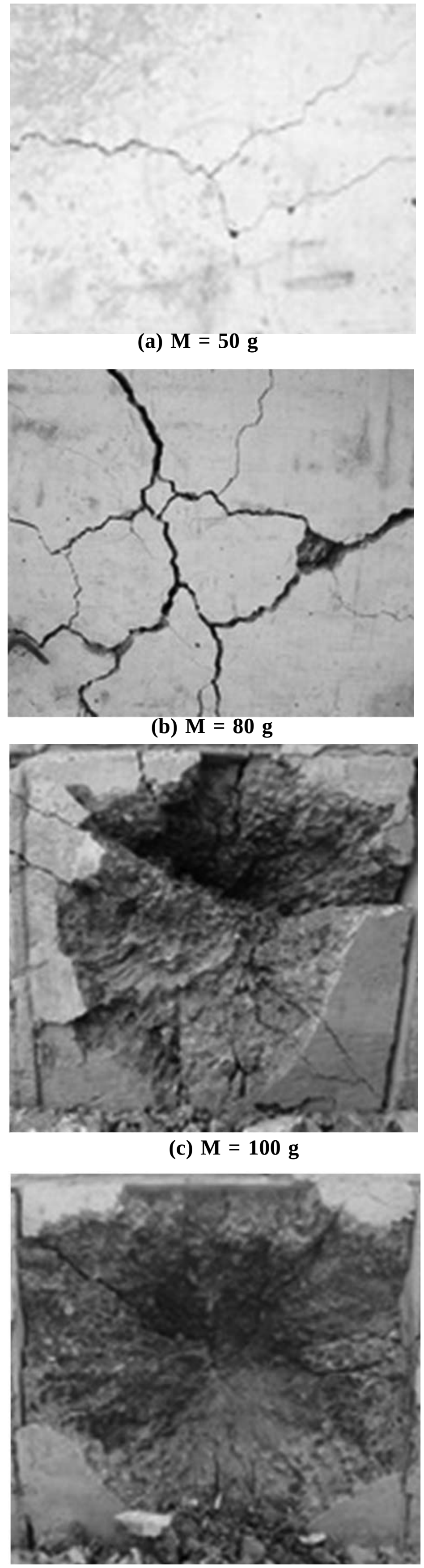
Table 2. Experimental data at the critical collapse states

h(*mm*)	*D*(*mm*)	M_c(*g*)	*L*(*mm*)	R_c(*mm*)
500	30	310	270.73	400
525	30	255	227.13	375
350	30	180	161.00	350
370	30	140	128.80	330
400	30	130	115.20	300
450	30	105	93.50	250
490	30	80	70.80	210
520	30	60	53.50	180

dimensional independent, and according to the Buckingham Π theorem Eqn.(1) can then be transformed into following dimensionless form:

$$\frac{R_c}{D} = f\left(\gamma, \frac{L}{D}, \frac{h}{D}; \frac{\rho_c}{\rho_e}, \frac{\sigma_t}{E}, \frac{\sigma_c}{E}, \mu\right) \quad (2)$$

In fact, damage and failure at the rear-surface of concrete targets is almost invariable with the same amount and geometrical properties of explosive charge when the depth of burial of explosive charge is large enough, which is satisfied in all these experiments. Dimensionless parameter *h/D* or the depth of burial of explosive charge *h* could not be taken into



(a) M = 50 g

(b) M = 80 g

(c) M = 100 g

(d) M = 110 g

Figure 4. Postmortem observation on the targets with the depth of burial *h* = 450 mm.

Table 3. Governing parameters in the internal explosion of finite concrete targets

	Variable	Dimension
Explosive charge	Density (ρ_e)	M/L^3
	Expansion coefficient (γ)	1
	Length (L)	L
	Diameter (D)	L
	Depth of burial (h)	L
	Specific energy (e)	L^2/T^2
	Detonation velocity (v)	L/T
Concrete	Density (ρ_c)	M/L^3
	Uniaxial tensile strength (σ_t)	M/LT^2
	Uniaxial compression strength (σ_c)	M/LT^2
	Elastic modulus (E)	M/LT^2
	Poisson's ratio (μ)	1

account. Moreover, for a given explosive charge and a target material, all the material parameters as well as corresponding dimensionless parameters are constant. Therefore, Eqn.(2) becomes:

$$\frac{R_c}{D} = f\left(\frac{L}{D}\right) \tag{3}$$

Combining with the experimental results presented above, the function f in Eqn.(3) can be determined by using the cubic polynomial fitting technique, in which the constant is too small and can be neglected. At the same time, for clarity, the fitted curve as well as the experimental results is depicted in Fig. 5, and the maximum relative error defined by the ratio of the absolute value of the difference between the experimental data and the fitted results to the experimental data is 6.0 per cent as shown in Table 4.

$$\frac{R_c}{D} = 3.993\frac{L}{D}\left[1 - 0.107\left(\frac{L}{D}\right) + 0.004\left(\frac{L}{D}\right)^2\right] \tag{4}$$

which is available in the range of $1.8 \le L/D \le 9.0$. Moreover, it can be seen from Eqn. (4) that the relative critical collapse thickness depends on both the amount and the length-to-diameter ratio of explosive charge, because the amount of explosive charge can be determined by the length-to-diameter ratio of explosive charge under certain density and diameter of explosive charge.

It was observed that relative critical collapse thickness was nonlinear and monotonic increasing function with respect to the length-to-diameter ratio of the explosive charge (or the amount of explosive charge for that the amount and the length-to-diameter ratio of explosive charge are interactional in some sense). And increasing tendency turns to be slower down after the length-to-diameter ratio of explosive charge is larger than 5, which implies that, for relatively larger length-to-diameter ratios, the energy dissipation will exert more and more influence on the relative critical collapse thickness, due to easily release of the explosion gas as well as redistribution of the explosion energy.

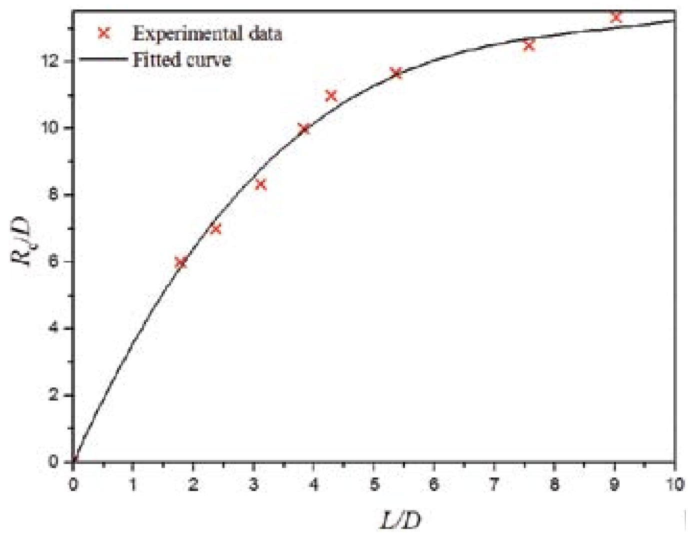


Figure 5. Relationship between R_c/D and L/D.

Table 4. Comparison of fitting results and experimental data

L/D	R_c/D Experimental data	R_c/D Fitted results	Relative error (%)
9.0	13.3	13.0	2.3
7.6	12.5	12.7	1.6
5.4	11.7	11.6	0.9
4.3	11.0	10.5	4.6
3.8	10.0	9.9	1.0
3.1	8.3	8.8	6.0
2.4	7.0	7.3	4.2
1.8	6.0	5.9	1.7

4. CONCLUSIONS

The critical collapse condition at the rear-surface of finite thickness targets of concrete under internal explosions was investigated experimentally in this paper. Both the critical collapse thicknesses and the critical amounts of explosive charge under eight different depths of burial were obtained. Combining the obtained experimental data with the dimensional analysis approach, the function relation between the critical collapse thickness and the length-to-diameter ratio of the explosive charge (the critical amount of the explosive charge) was obtained. It was found that relative critical collapse thickness was a nonlinear and monotonic increasing function of the length-to-diameter ratio or the amount of explosive charges and the increasing tendency turns to be slower after the length-to-diameter reaches upto 5. Length-to-diameter ratio of explosive charge has considerable effects on the rear-surface failure of concrete targets in finite thickness.

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