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A study on the cloud effect on debris trajectory

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Abstract

In this paper, the cloud effect on debris trajectory is investigated. The cloud effect discussed here refers to the reduction of the drag coefficients of debris at the initial stage of their trajectory after an internal explosion of an ammunition magazine, when the concrete magazine is just disintegrated into a cloud of closely packed concrete debris. The numerical results obtained with and without considering the cloud effect from the trajectory tracing tool DeThrow are used to study the influence on the debris initial landing position and kinetic energy. In addition, several different ways to simulate the influence of cloud effect are also discussed.

Keywords: debris trajectory, cloud effect, drag coefficient, DeThrow

Introduction

Inhabited Building Distance (IBD) from an unexpected explosion of an earth-covered magazine traditionally attracts lots of interest from researchers and defense staff. The IBD depends on the trajectory of the debris generated from the explosion. Besides gravity, the flying motion of debris is influenced by air drag, lift force and moment of the debris, while the air drag depends on many factors such as debris size, shape, surface area, maximum section area perpendicular to the motion direction, and velocity (Baker 2007, Richards et al. 2008, Song and Ou 2010, Richards 2012). In the initial stage of explosion, the reinforced concrete (RC) structural members break into pieces as a debris cloud. The aerodynamic coefficients of the debris fragments are affected by the presence of other debris in their vicinities. This is especially the case, if one fragment is in the slipstream of another. As the fragments progress outward, such cloud interference effect on the aerodynamic coefficients is reduced significantly. In order to calculate the trajectories of debris more accurately, such cloud effect should be taken into account.

Van der Voort et al. (2010) proposed an approach in which a debris cloud is treated as an entire wall as the air passing through the cloud is very minor. The drag coefficient thus *increases* as the virtual large block has worse aerodynamic properties compared with each small piece of debris. Helland et al. (2007) found that the drag decreases in diluted cluster and increases when the cluster density is high. Schlüter et al. (2013) studied the interaction between two pieces of debris. In their study, the cloud effect is categorized into two types: side-by-side effect and trailing-leading effect. The side-by-side effect *increases* the air drag acting on debris, while the trailing-leading effect *decreases* the air drag.

In this study, a simplified approach is adopted to investigate the cloud effect on the debris flight trajectory. In the simplified approach, a reduction function is multiplied with the air drag coefficient to simulate the cloud effect. The simplified approach is used in the Kasun test which is presented in (Fan et al. 2010) to study the cloud effect.

Flight equation

As shown in Figure 1, the flight equation can be written as (Tachikawa 1983, Tachihawa 1988, Chakraverty et al. 2001, Baker 2007):

$$M\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=M\frac{\mathrm{d}u}{\mathrm{d}t}=-\frac{A\rho}{2}\left(C_{\mathrm{D}}\cos\alpha+\left(C_{\mathrm{L}}+C_{\mathrm{LA}}\right)\sin\alpha\right)\left(u^2+v^2\right) \quad (1)$$

$$M\frac{\mathrm{d}^2y}{\mathrm{d}t^2}=M\frac{\mathrm{d}v}{\mathrm{d}t}=-\frac{A\rho}{2}\left(C_{\mathrm{D}}\sin\alpha+\left(C_{\mathrm{L}}+C_{\mathrm{LA}}\right)\cos\alpha\right)\left(u^2+v^2\right)-Mg \quad (2)$$

$$I\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}=M\frac{\mathrm{d}\omega}{\mathrm{d}t}=\frac{\left(C_{\mathrm{M}}+C_{\mathrm{MA}}\right)Al\rho}{2}\left(u^2+v^2\right) \quad (3)$$

where ρ is the air density, A is the projected area facing the flow, C_D, C_L, C_{LA}, C_M and C_{MA} are the coefficients of drag due to translational motion, lift due to translational motion, lift due to auto-rotation (magnus force), moment due to translational motion and moment due to auto-rotation (magnus moment), respectively.

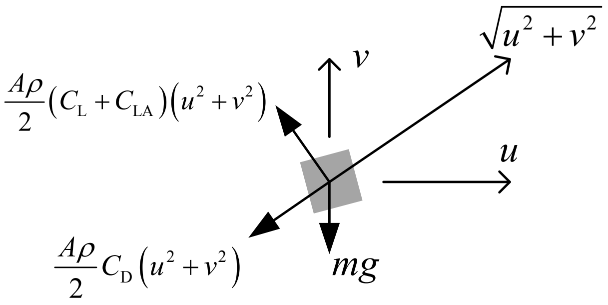


Figure 1. The flight state of debris

In the present study, the effect from C_M and C_{MA} are excluded. The coefficients C_D, C_L and C_{LA} are expressed as (Schlüter et al. 2013):

$$C_{\mathrm{D}}=S_{\mathrm{p}}C_{\mathrm{D,sphere}}+(1-S_{\mathrm{p}})C_{\mathrm{D,cube}} \quad (4)$$

$$C_{\mathrm{L}}=(1-S_{\mathrm{p}})C_{\mathrm{L,cube}} \quad (5)$$

$$C_{LA}=\frac{2\pi\omega R\alpha}{\alpha\sqrt{u^2+v^2}+190\pi\omega R} \quad (6)$$

In Eqs. (4) and (5), $S_p = (V_{debris}-V_{cube}) / (V_{ellipsoid}-V_{cube})$ is the debris sphericity, $C_{D,sphere}$ and $C_{D,cube}$ are the drag coefficients for spherical and cubic debris, respectively, and $C_{L,cube}$ is the lift coefficient for cubic debris. It should be noted that the lift coefficient for spherical debris is zero. In Eq. (6), R is the debris average radius, $\alpha = 2R/L_p$ is the aspect ratio and L_p is the longest size of the debris along the rotation axis. The detailed expressions of $C_{D,cube}$ and $C_{L,cube}$ are referred to (Schlüter et al. 2013).

Cloud effect

In a simulation, it is very hard to conduct a precise calculation on the air drag with cloud effect applying on each piece of debris. It is mainly due to the presence of a huge number (>100k) of debris which makes it extremely costly to trace the distances between each two pieces of debris at every time step during trajectory calculation. Thus, a simplified approach is employed to consider the cloud effect in the present study.

In the present study, a correction parameter χ is introduced into the algorithm. The coefficients of the air drag and lift with cloud effect can be written as

$$C_{\mathrm{D}} = \chi C_{\mathrm{D,free}},\ C_{\mathrm{L}} = \chi C_{\mathrm{L,free}} \text{ and } C_{\mathrm{LA}} = \chi C_{\mathrm{LA,free}} \tag{7}$$

where the subscript 'free' refers to the coefficient for individual debris without cloud effect.

As shown in Figure 2, in the debris cloud, most of the debris hides behind the front debris and the drag on the back debris is very minor. Hence, when considering cloud effect, the drag coefficient and the lift coefficients for most of the debris should have a smaller value.

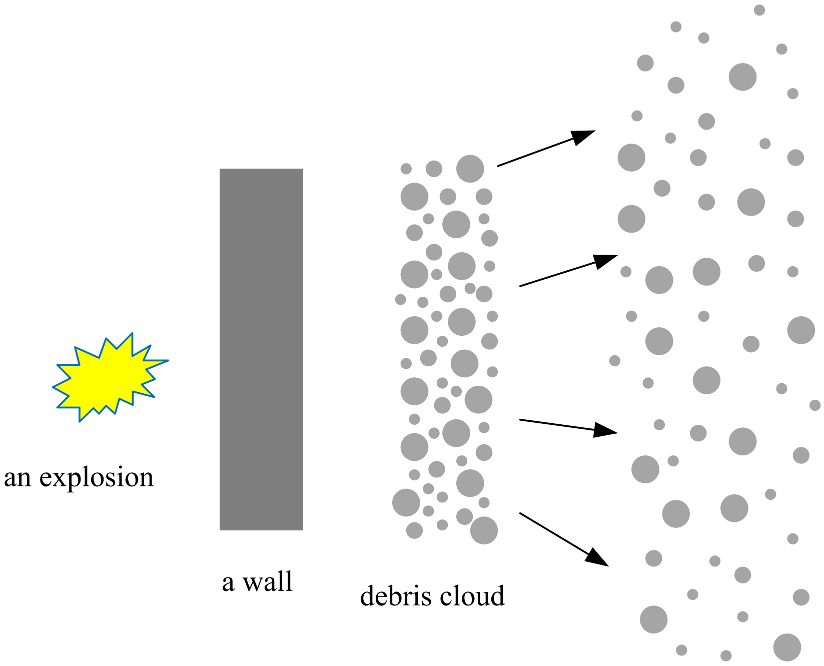


Figure 2. The debris cloud

In the present study, two kinds of reduction functions, namely a ramp function and a step function, are adopted to express the correction parameter χ as:

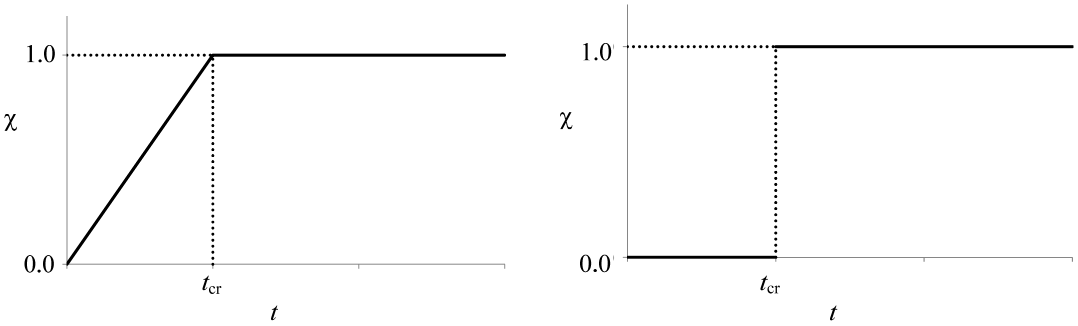
The ramp function:

$$\chi = \begin{cases} t/t_{\mathrm{cr}} & t \le t_{\mathrm{cr}} \\ 1.0 & t > t_{\mathrm{cr}} \end{cases} \tag{8}$$

and

The step function:
$$\chi = \begin{cases} 0.0 & t \le t_{\mathrm{cr}} \\ 1.0 & t > t_{\mathrm{cr}} \end{cases} \tag{9}$$

where t_{cr} is the critical time after which cloud effect is negligible. This parameter reflects the influence from the cloud effect on the air drag. The plots corresponding to Eqs. (8) and (9) are shown in Figure 3(a) and (b), respectively.



(a) The ramp function (b) The step function

Figure 3 The reduction function χ

Numerical results

In this section, the numerical simulation results are presented. The Kasun test presented in Fan et al. (2010) is employed in this study. The detonation is 2.5kg of TNT in the test. The numerical simulation for the disintegration of the magazine was conducted by the commercial package LS-DYNA. The numerical modelling was run for 0.008 second and the debris initial conditions at launching were collected for the present study.

Three cases are tested in the present study, including the case without cloud effect, the cases with the ramp function and the step function. For the two cases considering cloud effect, two critical time, t_{cr} = 0.1 second and 1.0 second, are used. It is noted that in the case without cloud effect, the average time for the debris first impact on the ground is around 3.2 second from the numerical simulation. Hence, t_{cr} = 1.0 second should be much greater than actual t_{cr} in the real test. However, as a numerical study on the influence from the parameter t_{cr}, the value of 1.0 can be regarded as an upper bound for the value of t_{cr}.

The two profiles of χ (the ramp function and the step function) and the values of t_{cr} (t_{cr} = 0.1s and 1s) are studied. The average horizontal distances of debris flight for the different numerical cases are listed in Table 1. In Table 1, two distances are listed for each case, where d_{c} is the average distance with cloud effect and d_{nc} is the average distance without cloud effect. The first impact refers to the distance that debris first impact on the ground, while the final location includes the ricochet of debris impacting on the ground. In Table 1, the values in the bracket are the relative differences in percent which are calculated by $\varepsilon = (d_{\mathrm{c}} - d_{\mathrm{nc}})/d_{\mathrm{nc}} \times 100\%$.

It can be found from Table 1 that the cloud effect has minor influence on the average horizontal distance of debris flight. The increase on the average distance is no more than 8%, even when the upper bound of t_{cr} (1s) is employed. On the other hand, the profile of χ does not influence on the average debris flight distance.

Table 1. The average horizontal distance of debris

	t_{cr} (s)	d_{nc} (m)	d_c (m)	
			the ramp function	the step function
the first impact	0.1	94.88	95.83 (1.00%)	96.42 (1.62%)
	1		101.98 (7.48%)	101.04 (6.49%)
the final location	0.1	100.94	101.84 (0.89%)	102.00 (1.05%)
	1		108.18 (7.17%)	107.46 (6.46%)

The distributions of the location of debris first impact on the ground for cases without cloud effect, with cloud effect for t_{cr} = 0.1s and 1s are shown in Figs. 4, 5 and 6, respectively.

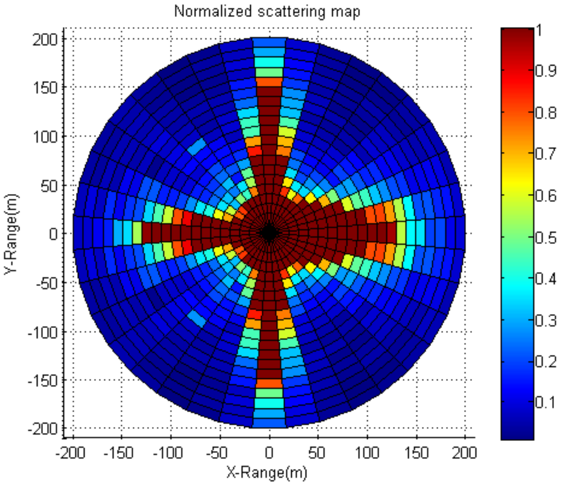
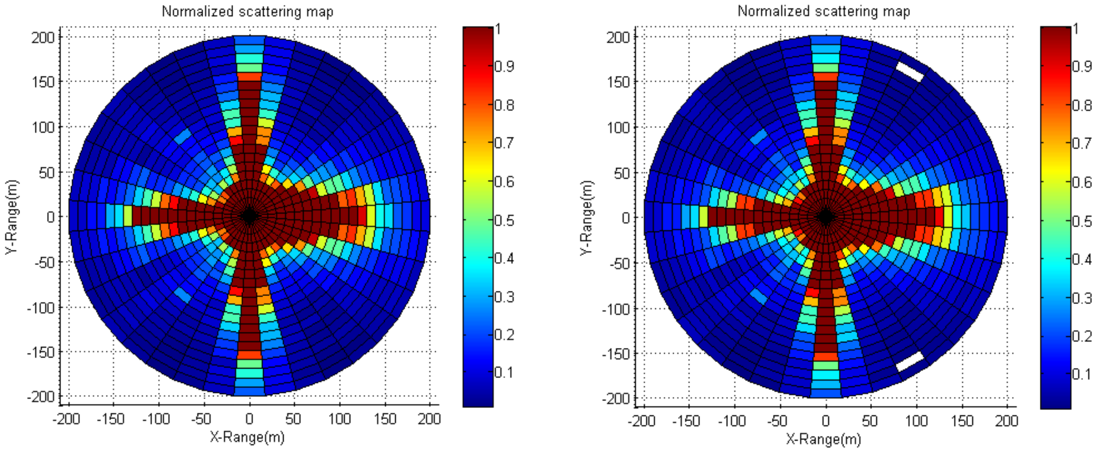
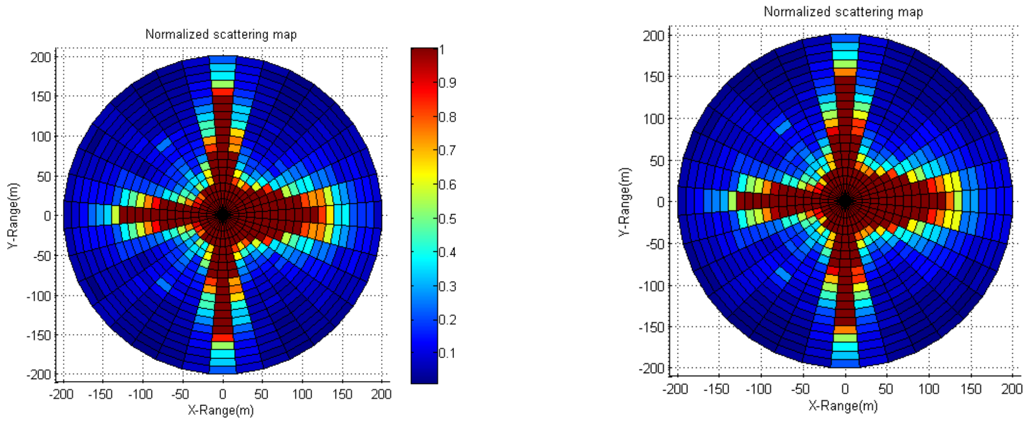


Figure 4. The location of the debris first hit without cloud effect



(a) The ramp function **(b) The step function**

Figure 5. The location of the debris first hit with t_{cr}=0.1s



(a) The ramp function **(b) The step function**

Figure 6. The location of the debris first hit with t_{cr}=1s

By comparing Figs. 5 and 6 with Fig. 4, it can also be found that the distribution of the debris first impact locations has shown a very minor change if the cloud effect is taken into account in the numerical analysis.

Conclusions

In this study, the cloud effect on the debris trajectory after an explosion is presented. As it is very costly to simulate the cloud effect at every time step, a simplified approach is employed. In the simplified approach, a reduction function is used to consider the reduction of air drag on debris. It is found that the cloud effect has only limited influence on the distribution of the debris flight trajectory.

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