Proposed Updates to the Siting Criteria of Heavy Earth Cover Magazines

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Abstract

Landuse limitations in Singapore has driven recent R&D efforts to look for innovative solutions to store explosives safely, as well as the capability to assess the explosive consequences more accurately so that areas surrounding ammunition could be better used. One of these programmes focuses on the development of Heavy Earth Covered Magazines (HECM). Based on prescriptive explosive safety codes, the minimum earth cover thickness required for Earth Covered Magazines (ECM) or Igloos is 0.6m. However, there may be potential to mitigate the explosive hazards using additional earth cover. Hence this HECM research programme has set out to have a better assessment of the explosive hazards related to munition storage in ECMs and to find better ways to reduce sterilised land. The programme aims to finally incorporate the findings into existing explosives storage standards and guidelines, such as the AASTP. From scaled tests on explosives storehouses, it was assessed that HECMs have the capability to reduce debris and blast hazards at the side and rear of the explosives storehouse. This paper describes two such tests. The results suggest the potential to safely develop more compact ammunition depots by adjusting the earth cover.

Introduction

Explosives storage is considered a high risk activity. Even if the probability of an accidental detonation is remote in many developed countries (Maniero and Rowland, 2009), the extreme consequences of these events make safe explosives storage a significant area of interest. Events such as recent explosions in Ukraine have reminded the explosive safety community of the devastating effect of accidental explosions from sites where large quantities of explosives have been packed into small areas, such as in an ammunition depot. Thus, in the master planning of many military camps and bases, ammunitions storehouses are sited a distance away from the critical military facilities, and even further away from the civilian population around these camps and bases. The approach of using distance to space out buildings to increase safety requires something which Singapore is short of – space. With a land area of about 700km^2, and 5 million inhabitants, Singapore has one of the highest population density in the world. As such, there is a strong impetus for the country to innovate to better use the limited space, while always maintaining high safety standards.

One of these innovations is the development of Underground Ammunition Facility (UAF), which is considered one of the most modern underground ammunition storage facility in the world. This facility enabled approximately 300ha of land, previously sterilized by conventional ammunition storage, to be freed. In order to cater for in-base aboveground ammunition storage requirement, the Defence Science and Technology Agency embarked on another research programme to build safer earth covered magazines with reduced explosives hazards, by increasing the earth cover thickness. The Allied Ammunition Storage Transportation Publication, AASTP-1, specifies a minimum inhabited building distance (IBD) of 400m for earth covered magazines (ECM). Such buildings must possess a minimum earth cover thickness of 0.6m (NATO, 2015). Noting that trials conducted by the Norwegian Defence Estate Agency (NDEA) on small scale earth covered structures yielded significant mitigation from additional earth cover (Grønsten, 2006; Øiom and Grønsten, 2008), DSTA embarked on an experimental programme to further study the effects of additional earth cover to reinforced concrete (RC) explosive storage magazines. The experiments will yield data such as the distribution of blast pressure and secondary (building) debris around the explosion site, to ascertain the hazard distances to a high fidelity. From this programme, and through collaborations with the international explosive safety expert panel, Klotz Group[1], DSTA hopes to contribute to having more options for safety enhancements of the guidelines in the AASTP publications by including thicker earth covered magazines.

In this study, three test series are planned; they differ primarily in the size of the test models. The loading densities studied, which is defined as the net explosive quantity (NEQ) divided by the internal volume of the magazine, vary between 2.5 to 20kg/m^3. Varying earth cover are also studied, representing between 0.6m to 2.4m thick covers in full scaled buildings. This paper aims to summarise the findings from the first two test series and propose the tentative new ECM siting recommendations for the AASTP publications.

Test Configuration

The experimental programme involves a total of nine tests models, spanning over three test series. The first and second test series which are described in this paper, were conducted with NDEA in Norway. A third test series is expected to be conducted in 2019. The details of test models, which are all earth covered RC structures subjected to internal detonation of bare charges, are tabulated in Table 1. Figure 1 and Figure 2 depict the actual test models from Test Series 1 and 2 respectively. As shown in the figures, the concrete of different structural components in each test model were dyed, to facilitate the documentation of the debris collection.

Table 1 Details of the ECM test models

Test Series	Test Model No	Internal Dimensions (Length x Width x Height) (m)	Wall Thickness (m)	Earth Cover Thickness (m)	NEQ (kg)	Loading Density (kg/m^3)
1	1-1	1.0 x 1.0 x 0.8	0.1	0.12	2	2.5
1	1-2	1.0 x 1.0 x 0.8	0.1	0.12	8	10
1	1-3	1.0 x 1.0 x 0.8	0.1	0.24	8	10
1	1-4	1.0 x 1.0 x 0.8	0.1	0.24	16	20
2	2-1	2.0 x 2.0 x 1.6	0.2	0.48	128	20
2	2-2	2.0 x 2.0 x 1.6	0.2	0.96	128	20
3	3-1	7.5 x 5.0 x 4.0	0.5	1.2	3,000	20

(a)

[1] The Klotz Group (KG) is an international body of explosives safety experts working on safety issues associated with the storage, processing and transport of ammunition and explosives. Membership comprises of technical experts from governmental defence agencies and research institutes from eight nations such as Germany, Norway, Singapore, Sweden, Switzerland, The Netherlands, United Kingdom and USA.

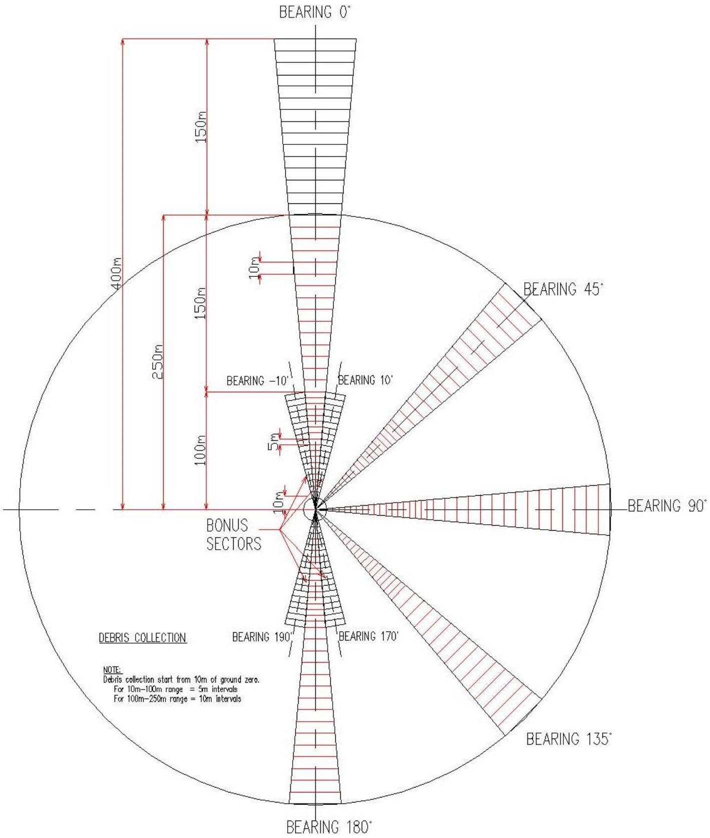
(b)
Figure 1 (a) Front view with earth cover and (b) rear view without earth cover of test models in Test Series 1

(a)

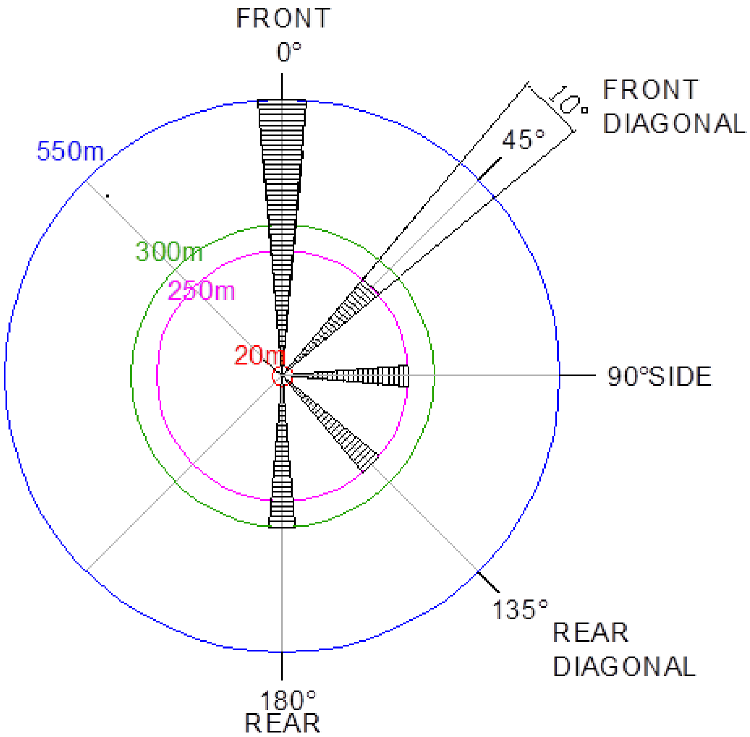
(b)
Figure 2 (a) Front view with earth cover and (b) rear view without earth cover of test models in Test Series 2

A comprehensive debris data collection plan was implemented in Test Series 1 and 2. Due to time constraints debris collection was not done over the entire areas surrounding all around the test buildings after each detonation. Instead concrete debris were collected along the principle axes radiating each detonation (front, side, rear), and along the diagonal axes (front diagonal, rear diagonal), in sectors of 10°. Collection commenced from ground zero, moving radially outwards at intervals of 10m for both Test Series 1 and 2. At each 10m interval point, debris was collected and bagged for cataloguing later. Each debris was then catalogued individually, according to the mass, color and the place (from point of detonation) where the debris was collected from was noted. In order to optimize the data collection effort, the minimum debris masses collected were 0.9g and 8g for Test Series 1 and

2 respectively (i.e. smaller debris was ignored). Such data will be analyzed qualitatively later, to ascertain the debris hazard distance from the models tested.



(a)



(b)

Figure 3 Debris collection sectors in Test Series (a) 1 and (b) 2

Each test was instrumented with pressure gauges which were surface-flush mounted on hard surfaces on ground (see Figure 4). Pressure gauges were distributed along the front, side and rear axes at distances tabulated in Table 2. Such data would be critical to ascertain the quantity distance, from which the IBD from the ECM would then be derived.

Table 2 Pressure gauge locations in Test Series 1 and 2

Test Series	**Distance from Ground Zero (m)**		
	Front	**Side**	**Rear**
1	10	5	5
	18	10	10
	25	20	20
	40	-	-
2	20	20	20
	40	40	40
	80	80	80
	160	160	160

Figure 4 Surface-flush mounted pressure gauges in Test Series 2

The last parameter of interest was the launch condition of the debris. This parameter may eventually be used to develop a consequence analysis tool, such as Klotz Group Engineering Tool, to assess the debris throws from an accidental detonation of ECMs (Van der Voort *et al*, 2010). This knowledge will also be used to develop measures to mitigate debris originating from certain parts of the ECM. As such, high speed cameras were setup to track the debris launched from the donor test models. These cameras were positioned by the side of each model building, to capture the response of the front wall, roof and door, and at the rear to capture the response of the roof. Response of the side and rear walls were not captured as they were still under the ballooning earth cover during the cameras' recording duration. Photographic markers shown in Figure 5 were installed to calibrate the videos captured for analysis.

Figure 5 Photographic markers along the side principle axis

Overall Structural Response

The overall structural response of the test models were generally similar in Test series 1 and 2 despite the difference in sizes. The front walls were pulverised but the roof, side walls and rear walls were sheared off at their edges. Both tests' roofs were launched almost vertically and landed in close proximity to ground zero. Variations in the final landing position was attributed to the onsite wind conditions. Figure 6 shows typical high speed video recording of the structural response. Table 3 tabulates the onsite observations after each test. It was observed that increased earth cover would reduce the distance, from the detonation point, where the side and rear walls landed.

(a) t = 0msec

(b) t = 66msec

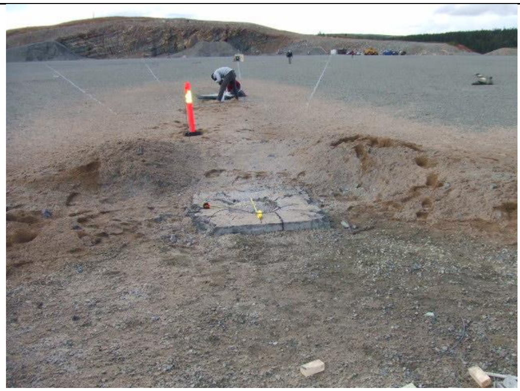
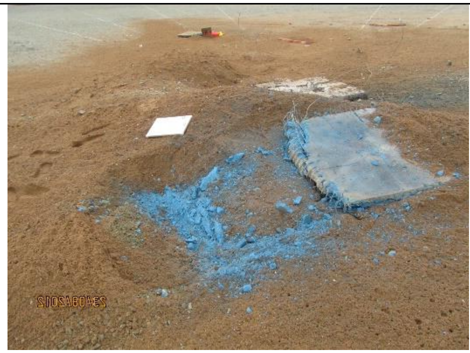
(c) t = 133msec

(d) t = 199msec

(e) t = 266msec

Figure 6 Image sequences of the structural response in recorded in Test Series 2

Table 3 Onsite photos of the test models after detonation

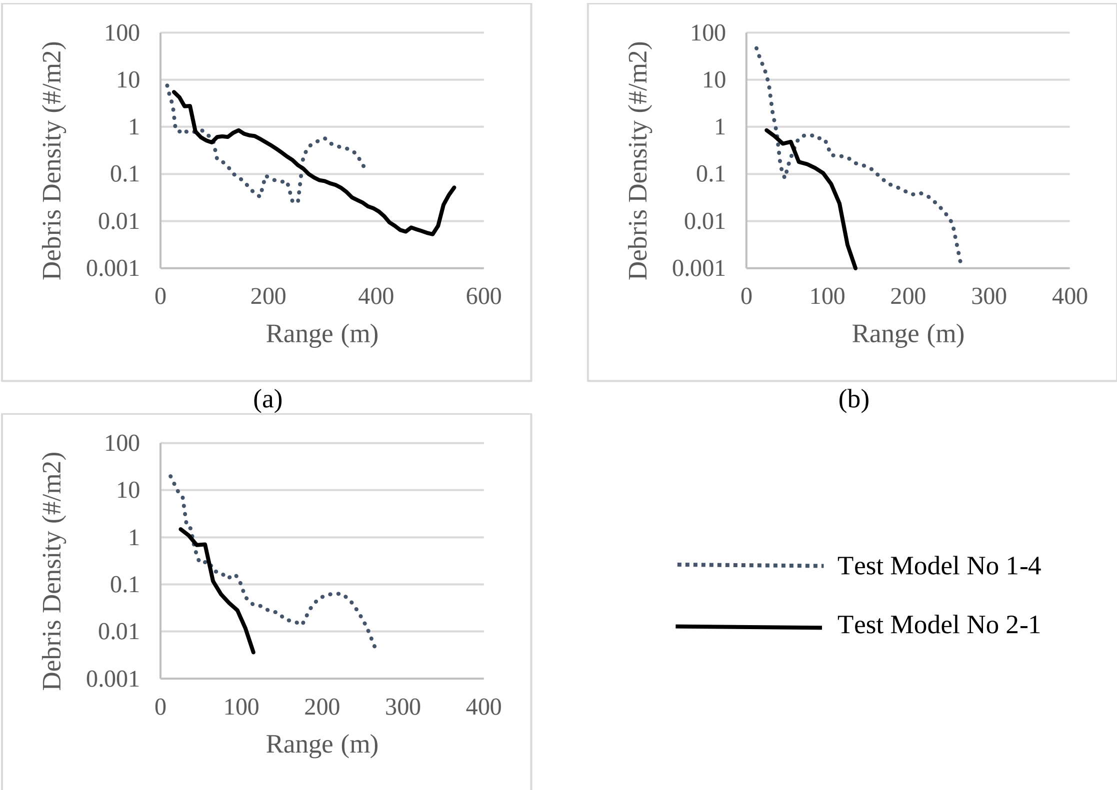
Test Model No	Front View	Side View	Rear View
1-1			
1-2			
1-3			

1-4			
2-1			
2-2			

Debris Data Analysis

Debris data indicated that the smaller test models in Test Series 1, launched debris further from point of detonation. Debris number density, which is defined as the number of debris collected divided by the area of the collection zone, from Test Model No 1-4 and 2-1, are compared in Figure 7 to illustrate this observation. Assuming Test Model No 2-1 is a scaled up version of Test No 1-4, the following observations are made:

a) A higher number of debris were generated from the smaller test model
b) Debris from the smaller test model were ejected further along the side and rear than the larger test model
c) Debris from the smaller test model were not projected as far along the front compared to the larger test model



(c)

Figure 7 Debris number density comparison between Test Model No 1-4 and 2-1 at the (a) front, (b) side and (c) rear

The observed differences between Test Series 1 and 2 can largely be attributed to the effects of gravity, which could not be scaled in these field tests. By the theory of replica scaling, under which Test Series 1 and 2 were designed, the ideally scaled gravity field for smaller structure should be higher than the gravity field of the larger scale tests, by the scale factor. However, as the gravity field of both tests were the same, the use of a lower than required gravitational force in Test Series 1: (a) allowed the smaller debris, which faced lower resistance from the earth cover during detonation of the explosives within the building, to be ejected from the earth cover at a higher velocity, and (b) projected the debris to greater horizontal distances. As a result, it was deduced that the debris data from Test Series 1 may have over represented debris throw when compared to Test Series 2 for the side and the rear, which was a larger scale. Conversely, the mitigation effects of earth cover on debris throw of Series 1, was under represented when compared to Series 2.

Quantitatively comparing the debris number densities from Test No 2-1 and 2-2 in Figure 8 and Figure 9, it can be observed that:

a) Earth cover thickness did not significantly affect the debris densities along the front axis
b) Earth cover thickness has a more pronounced debris mitigation effects at the side and rear
c) Debris generated at the front went beyond the minimum inhabited building distance of 400m for ECMs
d) Debris generated at the side and rear do not go beyond 200m, which is significantly less than the stipulated minimum IBD of 400m for ECM

As such, for loading density of 20kg/m^3 or less, there is potential to reduce the debris throw estimates at the side and rear of the ESH building to 200m. This in turn would result in a smaller IBD line around the ECM. Due to gravity scaling limitations and the importance of the IBD lines, this minimum distance will need to be verified in the conduct of Test Series 3, a full scale test. Debris throws from Test Series 3 will potentially be even smaller for similar loading densities in smaller scale tests, again, due to the limitation of scaling gravity in the earlier tests.

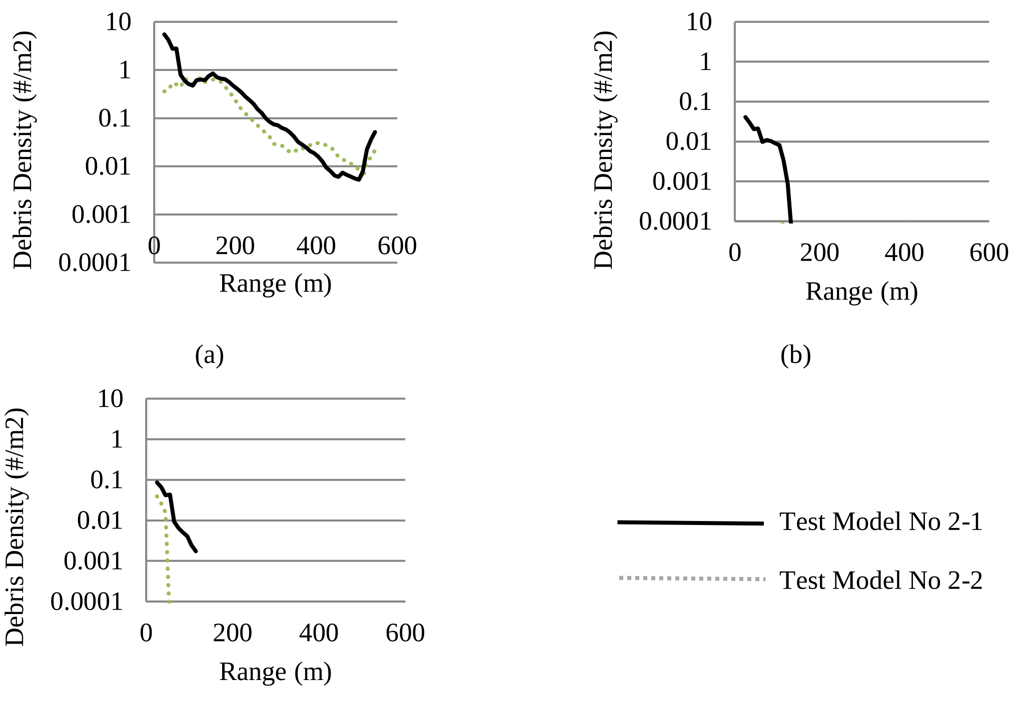


Figure 8 Debris number density comparison between Test Model 2-1 and 2-2 at the (a) front, (b) side and (c) rear

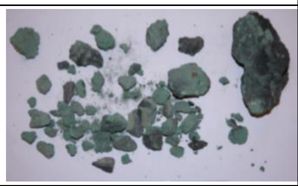
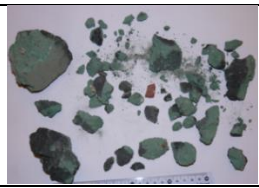
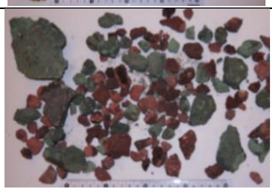
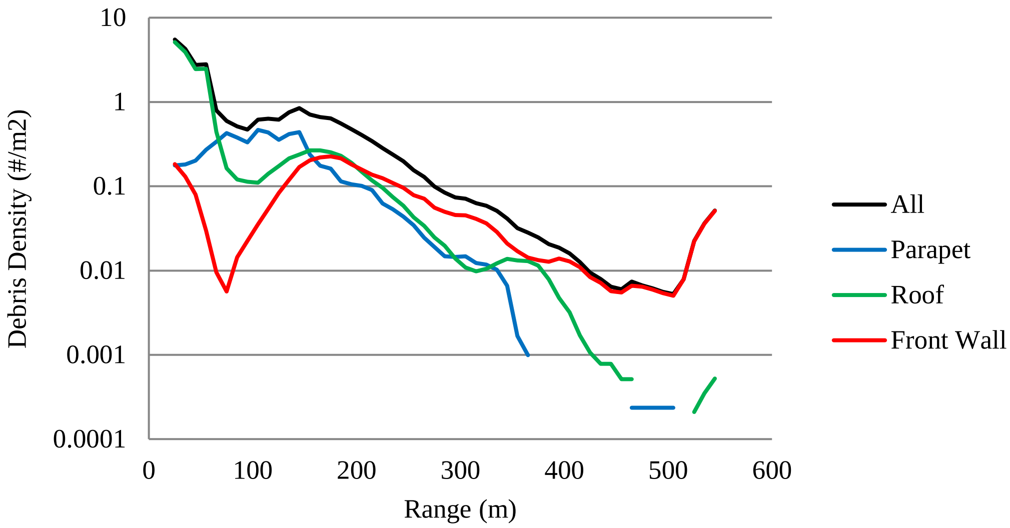
	Zone	Front	Side	Rear
Test No 2-1	50			
	100			-
Test No 2-2	50			
	100		-	-

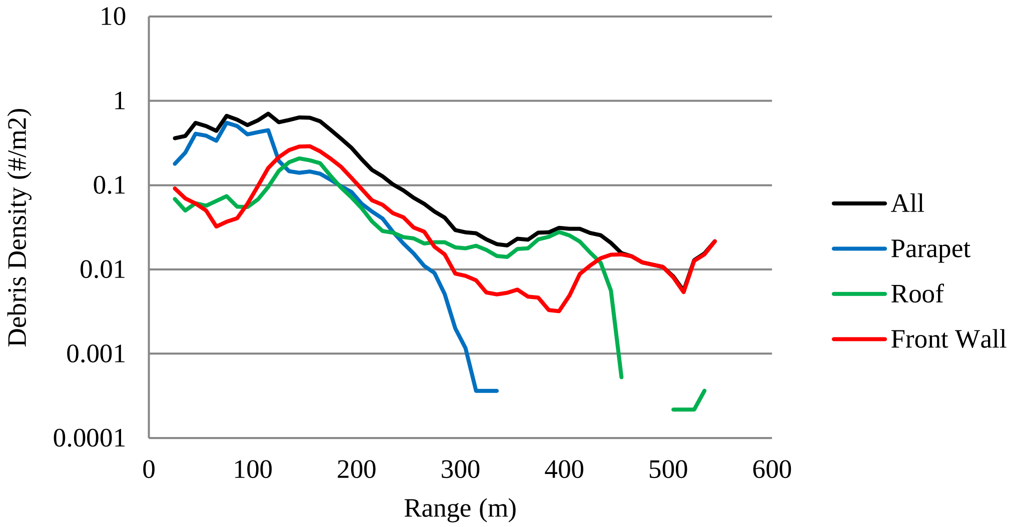
Figure 9 Comparison of the debris collected from Test No 2-1 and 2-2

As for the minimum debris throw (and consequently the minimum IBD) at the front, there is potentially a need to review the 400m limit. ECMs are commonly constructed with barricades in front of the buildings structure to mitigate the fragment from the stacked munition. Barricades may include earth traverses.

Upon deeper observations, the debris data along the front axis from Test No 2-1 and 2-2 can be further decomposed into their structural components - front wall, roof and parapet (see Figure 10). It is observed that the primary source of debris in the far field, comes from the front wall of the building. As such, barricades can be erected to mitigate the launch of the hazardous debris from the front wall to the front of the structure. The design height will be dependent on the launch angle of the debris. The subject of launch angle will be covered later in this paper.



(a)



(b)

Figure 10 Decomposition of the debris number densities along the front axis in Test Model No (a) 2-1 and (b) 2-2

Debris Launch Conditions

Using the high speed video footage, key structural elements were tracked to ascertain the launch velocities and angle. As seen in Figure 6, the door was first to exit the fireball. This was followed by a large debris from front wall. The last large piece of debris to exit the fireball was broken off from the blue parapet wall (earth retaining wall) above the door. Launch data collected are tabulated in Table 4.

Table 4 Launch velocities and angles of various large debris from the two tests

Test Model No	Launch Velocities (m/s)				Launch Angles (°)			
	Door	Front Wall (Red)	Retaining Wall (Blue)	Roof (Green)	Door	Front Wall (Red)	Retaining Wall (Blue)	Roof (Green)
2-1	260	127	35	67	6	12	58	89
2-2	285	135	28	40	8	12	63	86

While the increase in earth cover thickness did not significantly affect the launch conditions of the door, front wall and parapet wall, the roof velocity observed in Test Model No 2-1 was significantly higher than Test Model No 2-2. This can be attributed to the larger earth cover thickness. Coupled with the debris number density analysed in the preceding section, the launch angle of the door and front wall can be used to ascertain the height of the barricade. However, in order to obtain more representative data which is less affected by the limitation to scale gravity in such tests, to ascertain the minimum IBD (which is limited significantly by the debris throw phenomena), and due in a large part to large debris from components of the front wall, large scale tests are required. This is one of the main motivations to conduct Test Series 3.

It should be noted that gravity effects do not always overwhelmingly drive the determination of debris throw. Gravity effects, which limit scale tests observations of debris throw, tend to dominate more for small debris masses. For large debris pieces, the acceleration of these large debris, generated by the internal detonation, would reduce the influence of gravity. This can be observed when the roof launch debris is plotted against the scaled earth cover thickness (see Figure 11). Increasing the scaled earth cover does not reduce the roof launch velocity as sharply for the larger debris pieces (Test 2 series) as compared to the smaller debris (Test 1 series). The equivalent scaled earth cover thickness is defined as the earth cover thickness divided by the cube root of the net explosive quantity.

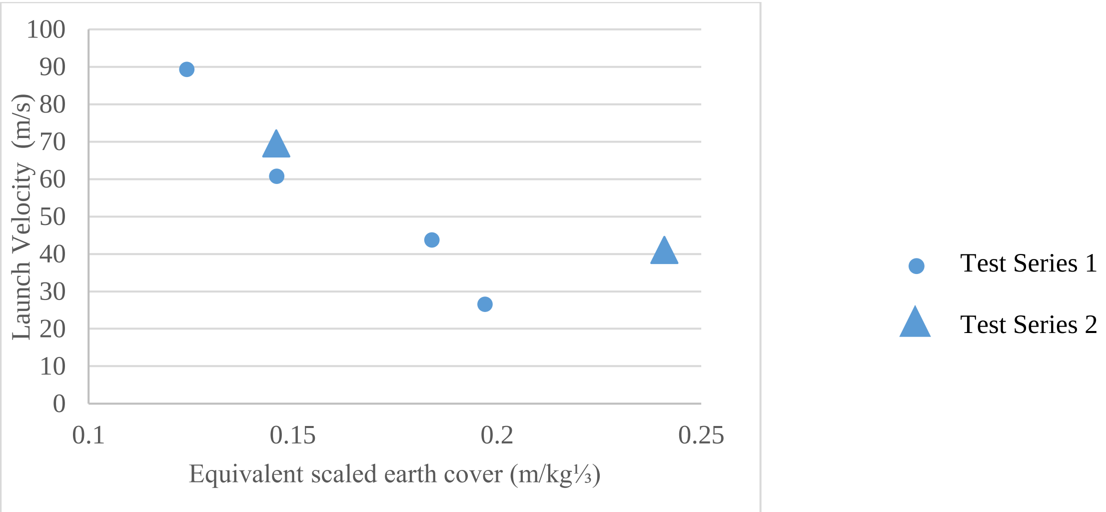


Figure 11 Launch velocities of roof debris in Test Series 1 and 2

<u>Blast Pressure Analysis</u>

The blast pressure levels, which limit IBD lines, can be derived from the pressure records from the gauges specified in the preceding section. Based on the criteria of a peak pressure of 5kPa, and by plotting this peak pressure against scaled distance, the quantity distance (QD) to determine the IBD (NATO, 2015) can be derived.

QDs for ECM are believed to be based on past tests of a higher explosive quantity or loading density. A previous study was conducted to compare the recommended QD for IBD from Test Series 1 and 2 against recommendations from the AASTP (Lai *et al*, 2017). These findings, compared with recommended QD for blast IBD from AASTP-1 and AASTP-4, are summarised in the table 5 below.

Table 5 QD for IBD based on AASTP and Test Series 1 and 2

	Quantity Distance (m/kg$^{1/3}$)			
	IBD based on AASTP-4	**IBD based on AASTP-1**	**Average IBD based on Tests with Loading Density of 10kg/m^3**	**Average IBD based on Tests with Loading Density of 20kg/m^3**
Front	18.4	22.2	22.6	20
Side	18.6	18	14.9	14
Rear	15.5	14	-	12

The following observations can be deduced from this table above:

a) The front IBD in Test Series 1 and 2 were found to be higher than the side and rear IBD. This is aligned with the trends in AASTP-1. However, this is not reflected in AASTP-4 as the data used to derive the variation of peak pressure with distance is based on higher loading densities (55-264kg/m^3). In those cases, the attenuation effect of earth cover may not possess significant blast mitigation.

b) In increasing the explosive quantity, the front IBD decreases. This is attributed to the blast channeling effect of the earth cover. With a lower earth cover and higher NEQ, due to the breakup of the structure, this channeling effect is reduced. This is also aligned with the observation in the preceding point.

c) There is some evidence that the loading density does not significantly affect the side IBD. However, this is not evident for the rear due to the lack of data collected from the tests.

d) Comparing the recommendations with AASTP-1 and test data, the front IBD is not significantly different. The side and rear IBD can potentially be reduced up to 22% and 14% respectively.

Recommendations

The ongoing experimental programme has indicated differences from the IBD recommendations in the AASTP publication. As such, potential changes to the current recommendations for ECMs in the AASTP are proposed.

Through these tests, it can be deduced that the existing minimum distance of 400m which is based on debris hazard throw, is potentially lower (conservative) for the side and rear under the loading density studied. This is due to the fact that the magazine wall and roof are not pulverized, but are ejected as a single large piece as observed from Test Series 1 and 2. These structural components are expected to land in close proximity to the magazine. However, it is not conservative to adopt the current minimum IBD for the front. Nevertheless, a barricade at the front could potentially catch or deflect the debris originating from the front wall and door. The launch angles of the front wall debris was observed to be 12 degree, as shown in Figure 4. Thus, it is recommended that the height of the barricade or earth traverse be based on 12 degree angle from the soffit of the roof of the ECM, as illustrated in

Figure 12. This may allow us to retain the minimum IBD of 400m for the front. This knowledge gap together with an eventual recommendation on the minimum side and rear IBD will potentially be bridged in the conduct of a full scale ECM in Test Series 3.

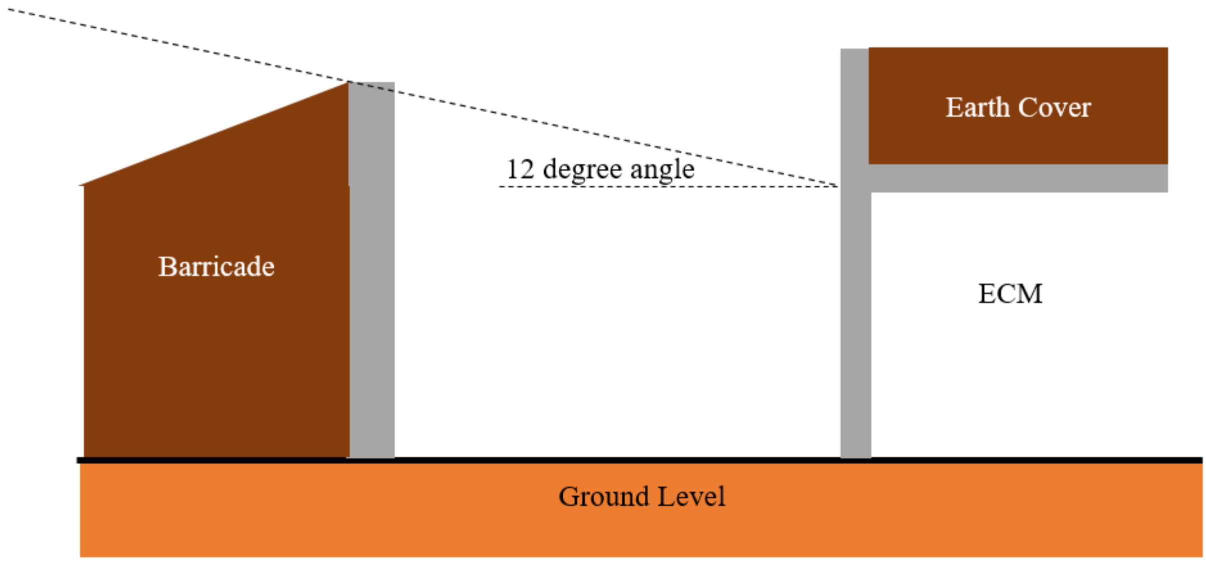


Figure 12 Illustration to determine the height of the barricade or earth traverse

In terms of the QD for IBD, it is recommended to consider the values proposed in Table 5, but with the loading density for use of values in Table 5 limited to cases with a loading density upper bound of 20kg/m^3. Similar to the recommendation on the minimum IBD, this amendment to the AASTP-1 would be validated through Test Series 3.

Conclusion

DSTA has embarked on an experimental programme to investigate the mitigation effects of earth cover on RC ammunition storage magazines. Of the three series planned, the conduct of Test Series 1 and 2 have been completed and these have indicated potential areas for improvement from the siting recommendations of ECMs set out in the AASTP-1. While there is potential to reduce the minimum IBD at the side and rear sectors, it was shown that this guideline may not be conservative for the front sector. A recommendation on the design of the barricade in front of the ECM may potentially resolve this issue. Amendments to the side and rear QD of ECM are also recommended. They will be validated in the full scale test in Test Series 3.

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Figures and Tables