Engineering Explosive Safety – Development of the Pseudo Underground Storage Structure (PUGSS)

C.C. Seah; Defence Science and Technology Agency; Singapore

W.T. Toh; Defence Science and Technology Agency; Singapore

H.S. Lim; Defence Science and Technology Agency; Singapore

Y. Kim; Naval Facilities Engineering and Expeditionary Warfare Center; United States

K. Hager; Naval Facilities Engineering and Expeditionary Warfare Center; United States

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Abstract

There are many challenges when it comes to ensuring the safe storage of ammunitions in areas with high density population, infrastructure development, or limited land availability in military installations. The scarcity of land in Singapore has motivated the development of new technologies to overcome these challenges. In recent years, DSTA had collaborated with NAVFAC EXWC to design and develop the Blast Resistant Wall (BRW) technology and the Pseudo Underground Storage Structure (PUGSS) to reduce encumbered land for ammunition storage when using conventional aboveground magazines. PUGSS is a specially engineered containment structure with BRWs and a hardened roof that are capable of withstanding the internal explosion effects of ammunitions stored within, and limit the damaging effects to the surrounding exposed sites (ES). This new type of engineered containment structure has also raised the practical limit of the loading density or "charge weight to room volume ratio" of the design of a reinforced concrete (RC) containment structure of maximum 2.4 kg/m^3 documented in the US Department of Defense (DoD) Unified Facilities Criteria (UFC) 3-340-02 to 9.23 kg/m^3. Starting with the principles behind the BRW design, the paper delves into systematic process of developing the PUGSS storage cell which design has been validated through an explosive test of a half-scale structure. The paper also presents the possible applications of the BRW technology and PUGSS.

Introduction

With a land area of about 720km^2 and population of 5.7 million, Singapore is one of the most densely populated country in the world. Besides catering land for residential, commercial and industrial purposes, there is also a need to set aside land for military infrastructure and training.

Storing ammunition safely is one of the challenges that the Singapore Armed Forces (SAF) face. Large amount of valuable land around each of the ammunition storage facilities has to be sterilised for explosive safety reasons. Due to Singapore's land scarcity, there is a strong impetus for the country to innovate in order to overcome the land constraint with new technologies that can reduce hazards arising from the unlikely event of an accidental explosions in ammunition storage facilities. One of these innovations is the development of engineered containment structures for ammunition storage.

Engineered containment structures are buildings with hardened structural elements that are capable of withstanding the internal explosion effects of ammunitions stored within, thus limiting the damaging effects of the potential explosion site (PES) to the surrounding environment. Procedures for designing engineered reinforced concrete (RC) containment structures are documented in the US Department of Defense (DoD) Unified Facilities Criteria (UFC) 3-340-02 [1]. However, the practicality of the design of a RC containment structure is limited by the loading density or "charge weight to room volume ratio" of maximum 2.4 kg/m^3. This means that a large structure is necessary to contain a small quantity of explosives which is not economically practical. To overcome this limitation of conventional engineered containment structures, DSTA collaborated with NAVFAC EXWC to develop the Singapore High Performance Magazine (HPM) [2] in the late 1990s using the database from NAVFAC EXWC's HPM and Non-Propagation Wall (NPW) test programmes. Ammunitions are stored in cells in the Singapore HPM (see Figure 1), and has a maximum credible event (MCE) of 1 tonne, which is the storage capacity of each cell. To push the design boundary of the Singapore HPM further, DSTA had in recent years collaborated with NACFAC EXWC to design and develop the Blast Resistant Wall (BRW) technology and the Pseudo Underground Storage Structure (PUGSS) which has a storage capacity of 5 tonnes per cell and loading density of 9.23 kg/m^3 in each storage cell.

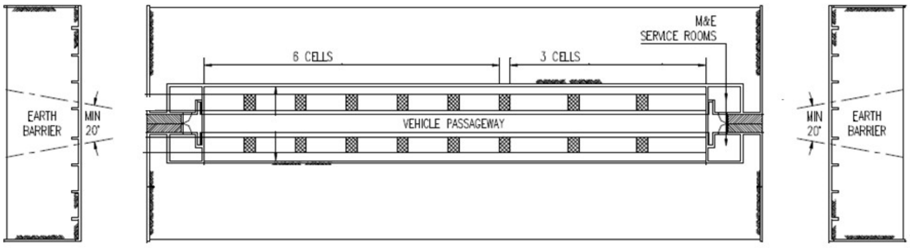


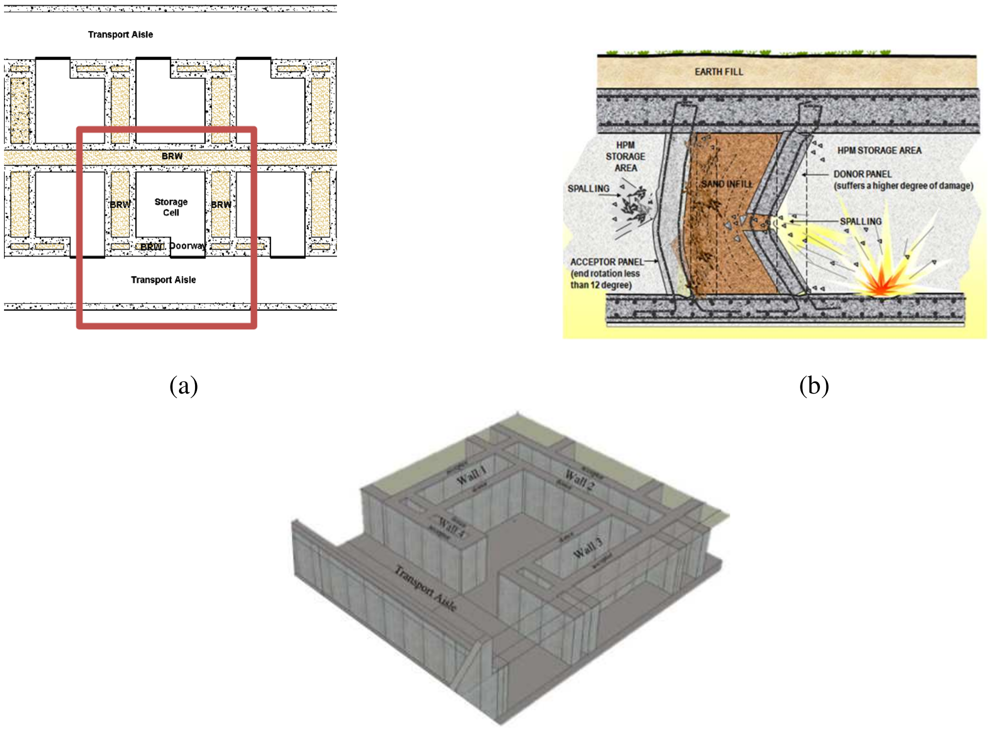
Figure 1 Plan view of the Singapore HPM [2]

PUGSS and BRW

Similar to the Singapore HPM, the PUGSS consists of a series of storage cells, separated by blast resistant walls (BRW) as shown in Figure 2(a). The PUGSS roof comprises a heavily reinforced concrete slab with soil cover. In case of a detonation in a single storage cell, the BRWs prevent propagation of detonation between storage cells as illustrated in Figure 2(b), and the roof slab with the soil cover mitigates exterior hazardous debris and pressure.

Figure 2(c) shows an isometric view of a typical storage cell of the PUGSS with the roof slab and soil cover removed. Sand located in the cavities of the four BRWs is also removed for clarity. The critical structural components of the PUGSS storage cell include the four BRWs, the roof slab, the transport aisle and exterior retaining walls. Walls 1, 2 and 3 represent the BRWs separating the donor storage cell from adjacent storage cells. Wall 4 represents the BRW separating the storage cells from the transport aisle.

The BRWs are defined as composite construction with granular material sandwiched between two reinforced concrete (RC) panels. The two reinforced concrete panels are referred to as the donor panel, which is located on the blast side of the BRW, and the acceptor panel, which is located on the protected side of the BRW. The composite BRWs resist the blast loads by: (1) increasing mass in the BRW with increased thickness of the sand and (2) reduction of blast pressures on the acceptor concrete panel by movement and compression of the sand fill.



(a)

(b)

(c)

Figure 2 (a) Conceptual design of PUGGS, (b) BRW technology, and (c) typical storage cell of PUGSS

Each panel is connected to an adjacent BRW and the roof and floor slabs. Each panel in Walls 1 through 4 were designed according to UFC 3-340-02 criteria as two-way elements with a negative moment along four supported edges. Wall 4 was designed as a two-way element supported on three edges and one free-edge. Though designed to be compliant with UFC 3-340-02 criteria, the original design resulted in excessive calculated support rotations in response to the expected blast loads calculated using SHOCK [3] and FRANG [4], which are computer programmes to generate the design charts for shock and gas pressures in UFC 3-340-02. To reduce the calculated support rotations, the resistance function was modified to account for compression membrane effects based on the criteria in UFC 3-340-01 [5]. Figure 3 compares the resistance functions based on flexural resistance and flexural combined with compression membrane resistance. By accounting for compression membrane effects, the strain energy absorbed by a RC panel increases by 140%. The resistance functions calculated using SBEDS [6] and per UFC 3-340-01 are in good agreement. By accounting for compression membrane effects, the calculated support rotations for the BRWs were reduced to less than 12 degrees, which is the design limit set for the BRWs.

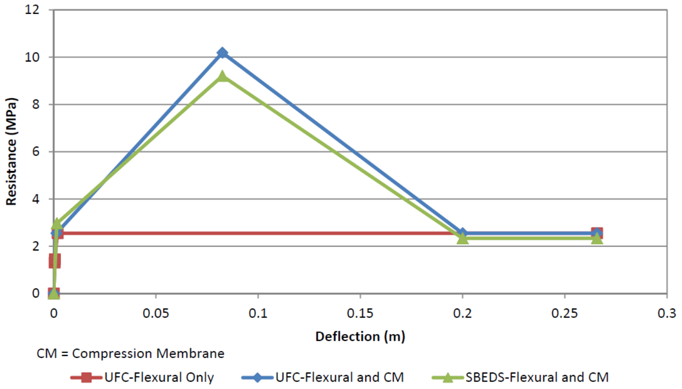
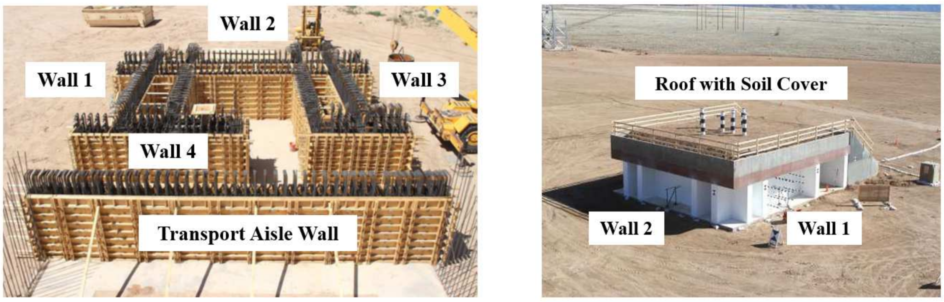


Figure 3 Comparison of resistance functions based on flexural resistance and compression membrane-enhanced flexural resistance in the design of the BRW RC panels [7]

In order to validate the PUGGS concept and BRW design to withstand the high loading density of 9.23 kg/m^3 in each storage cell, DSTA and NAVFAC EXWC conducted an explosive test of a half-scale single storage cell model of the PUGSS. The primary objective of the half-scale test was to validate the design methodology and response of the BRWs. The secondary objectives included determining the explosives safety siting distances for external blast pressure and debris throw, and determining the constructability of the BRWs.

Scaled Explosive Validation Test

The test structure was a half-scale model of a single storage cell of the PUGSS with a partial length of the transport aisle. Figure 4 shows the test structure under construction and when it was completed for the explosive test. The as-built test structure is a heavily reinforced concrete structure. The reinforcement ratio, which represents the ratio of the reinforcement to the effective area of the concrete, is 0.0335 for the BRW panels. The internal dimension of the scaled storage cell is approximately 5.45 m x 5.2 m, with a floor to ceiling height of 2.5 m. The four BRWs have different sand fill thicknesses to examine its effectiveness in reducing blast loads on the acceptor panel with increasing sand thickness and weight. The dimensions of the BRWs are summarised in Table 1 below.



(a) (b)

Figure 4 Half-scale model of a single storage cell of the PUGSS (a) under construction and (b) when completed for the explosive test [8]

Table 1 Geometric Properties of the Blast Resistance Walls

Blast Resistance Wall No.	Thickness of Blast Resistance Wall Component (m)			Blast Resistant Wall Dimension (m)	
	Concrete Donor Panel	Sand Fill	Concrete Acceptor Panel	Length	Height
1	0.575	1.4	0.575	5.2	2.5
2	0.575	1.15	0.575	5.45	2.5
3	0.575	1.15	0.575	5.2	2.5
4	0.575	0.4	0.575	2.78	2.5

The roof slab was designed to provide adequate lateral restraints at the joints where a concrete panel frames into a continuous roof, for compression membrane action. The thickness of the soil cover above the roof slab was not only to lower initial debris launch velocity but also to satisfy the underground explosive storage criteria for debris arising from the failure of cover or crater debris using Part III of the Manual of NATO Safety Principles for the Storage of Military Ammunition and Explosives (AASTP-1) [9]. The crater debris criteria is only applicable when the minimum distance from the perimeter of a storage cell to an exterior surface exceeds $0.10Q^{1/3}$, where Q is the explosive quantity in kg. With a design net explosive quantity (NEQ) of 750kg for the test, the minimum required cover thickness was 0.91m. Through analysis of the structural response, the roof slab was designed to be 0.75 m with a soil cover thickness of 1.25 m.

The design NEQ of 750 kg accounted for the safety factor of 1.20 required by UFC 3-340-02 for the maximum credible event (MCE) of 625 kg for the half-scale model of the PUGSS storage cell (which MCE is 5 tonne). The explosives used in the test is Composition-4 (C-4) for which the TNT equivalency factor is 1.3 (average of TNT equivalent weight for shock pressure, impulse and quasi-static pressure). The total of 577 kg of C-4 bricks was equally distributed into four rectangular stacks and detonated simultaneously within the storage cell as illustrated in Figure 5. These charges were located parallel with Wall 1 at a distance of 1.39 m from this wall. Spacing between the charges and Walls 2 and 4 was even at 1.04 m. The centre of the charges was located 1.39 m from the donor panel of Wall 1 and 0.5 m above the floor. The nominal loading density of the storage cell was calculated to be 9.23 kg/m^3.

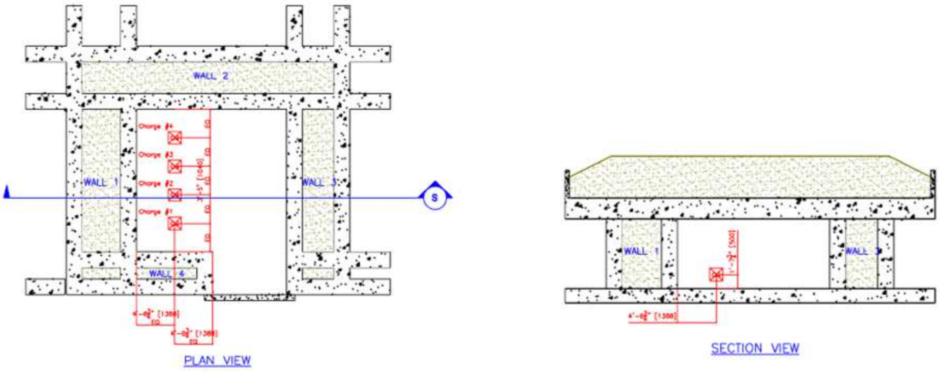


Figure 5 Plan view and section view of the test structure and placement of explosive charges for the test [10]

The test structure was instrumented with pressure gauges, including soil pressure and quasi-static, accelerometers, linear variable differential transformers (LVDTs) and thermocouples. A total of 36 measurements were recorded during the test. The objectives of the instrumentation were: (1) to provide test data to understand the response of the BRWs (2) to measure the blast load environment throughout the test article to compare to the loads used in the pre-test calculations, and (3) to assess the effectiveness of the sand fill between the concrete panels of the BRWs.

Results and Post Test Analysis

Figure 6 shows series of still images from the explosive test. The blast wave and the fire ball are observed to exit the test structure via the two openings of the transport aisle. At a further distance away from the test structure, the blast wave can be seen propagating outwards in a circular manner.

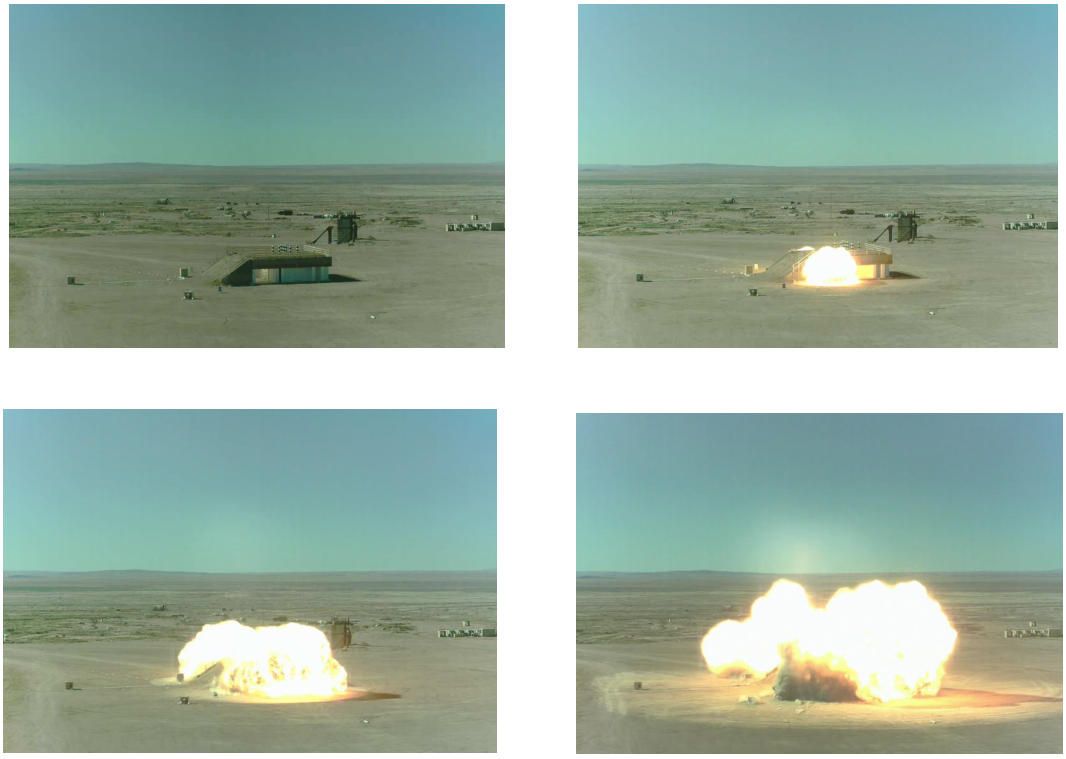
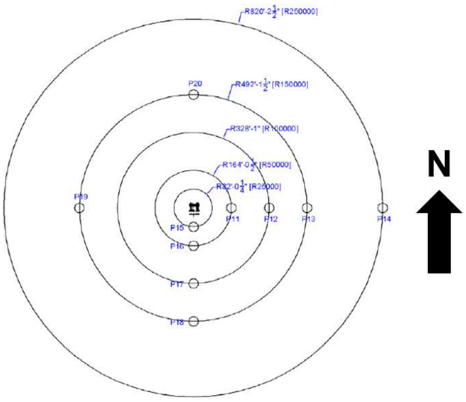


Figure 6 Still images from the explosive test showing blast wave and fire ball propagation

Figure 7 shows the locations of far-field pressure gauges used in the explosive test and the peak free-field pressures recorded from the test. The readings indicated that the test structure has a radial inhabited building distance (IBD) of 150m for the blast pressure criteria of 5kPa. This air blast IBD is 25% shorter as compare to a conventional aboveground ammunition magazine of similar NEQ (of 750kg), which air blast IBD is given by $22.2Q^{1/3}$ or 750m, where Q is the NEQ in kg.



Gauge No.	Gauge Description	Peak Free-Field Pressure (kPa)
11	East, R = 50m	41.9
12	East, R = 100m	12.5
13	East, R = 150m	5.3
14	East, R = 250m	3.0
15	South, R = 25m	34.3
16	South, R = 50m	17.8
17	South, R = 100m	8.7
18	South, R = 150m	4.6
19	West, R= 150m	5.6
20	North, R = 150m	5.3

Figure 7 Locations of the far field pressure gauges and recorded free-field pressures [10]

Figure 8 shows that the test structure remained essentially intact after the detonation of the explosive charges. The soil cover on the roof slab was largely in place as shown in Figure 8(a). A series of still images capturing the ejection of debris and soil cover from the roof of the test structure are shown in Figure 9. High speed video footages for the test measured maximum vertical velocities of 21 m/s for the roof ejecta. The throw distance of the debris and soil cover from the roof are found to be within 30.5 m from the exterior faces of the test structure (see Figure 10).

Figure 8(b) shows the top of the roof slab with the soil cover removed after the test. Fracturing and breakup of the concrete occurred above the storage cell and above a large area of the transport aisle. The damage area extended to the acceptor panels of Wall 1 through 3. The size of the concrete debris was typically 150 mm or less. Beyond the acceptor panels of these three walls, cracks were observed, though the concrete remained in place. It was observed that the RC roof thickness of 0.75m with 1.25m of soil cover was capable of preventing a breach of the test structure roof, and allowed the internal blast pressure and debris to exit from the two openings of the transport aisle.

Figure 8 Post-test views of the test structure showing Wall 1 and the roof with (a) soil cover and (b) soil cover removed after the test [7]

Figure 9 Still images from the explosive test showing the ejection of debris and soil from the roof of test structure

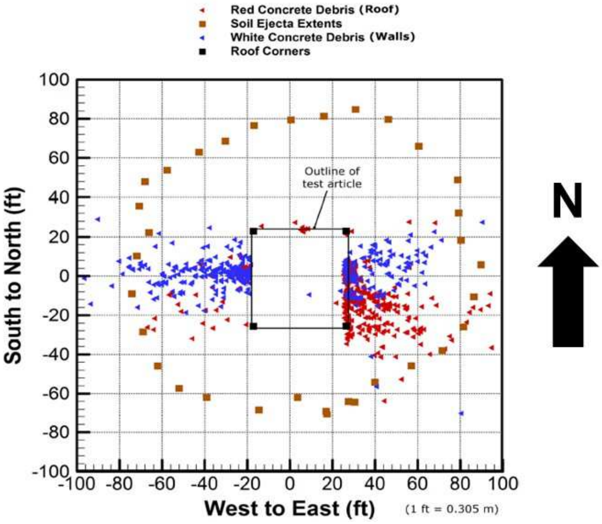
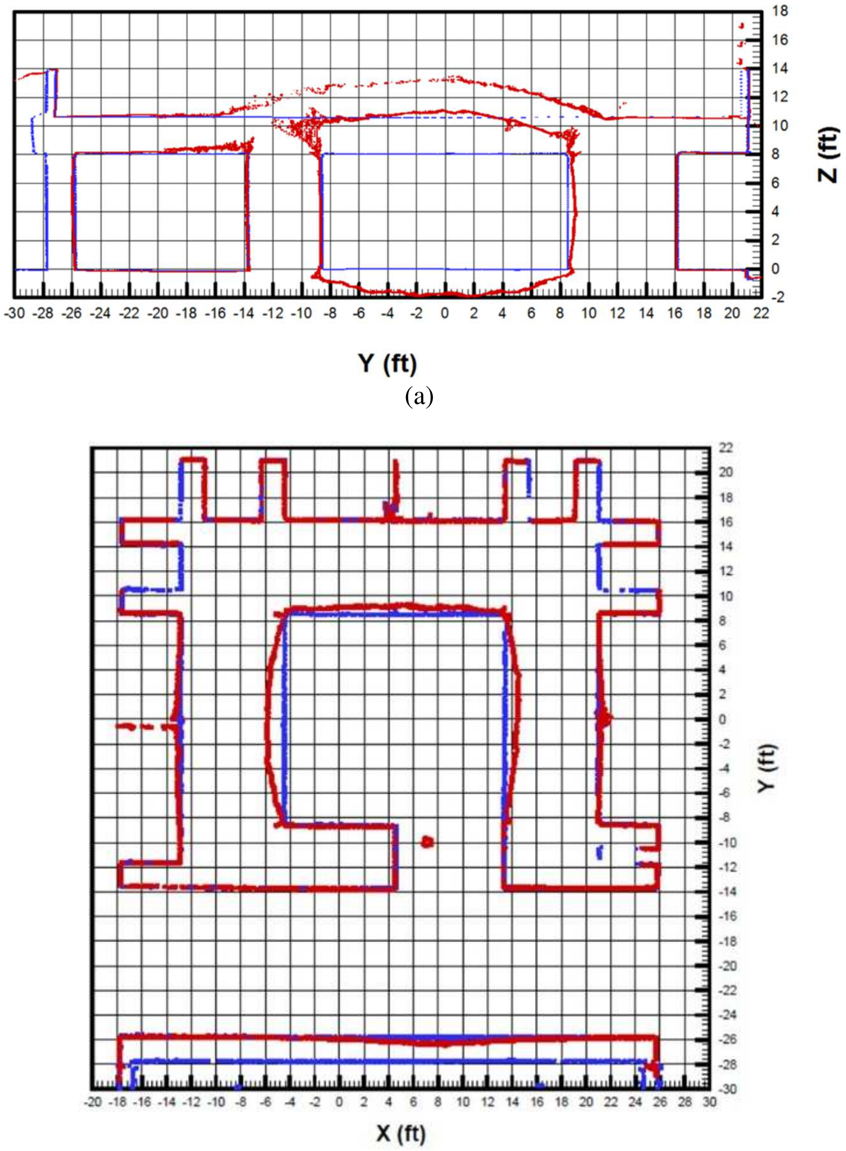


Figure 10 Throw distances of soil cover and debris from the roof and acceptor panels of the BRWs [7]

Data collected from LIDAR survey were used to study the deformation of the test structure (see Figure 11). The permanent displacement of the roof slab was found to occur along the plane at the origin at ground zero (Y = 0 point in Figure 11), and the displacement was 0.92 m, that is, the support rotation of 19.5 degrees. Due to the geometry (aspect ratio of greater than 1 but less than 2) of the roof slab, sufficient lateral restraint could be applied to develop in-plane forces and induce tension membrane action. This tension membrane action provided the means for the roof slab to attain deflections corresponding to a maximum support rotation in excess of 12 degrees without being breached.



(a)

(b)

Figure 11 LIDAR survey data showing (a) elevation and (b) plan view of the deformation of test structure [8]

Inside the test structure where the explosives charges were detonated, Figure 12 shows the gap, which opened between the top and bottom of the donor panel of Wall 1 and the floor and roof slabs, and typical failure of the vertical reinforcing steel. The gaps are representative of the failure mode that developed between the donor panels of Wall 1 through 3 and the floor and roof slabs. The post-test inspection of the reinforcing steel in Wall 1 donor panel showed that 106 of the 170 vertical bars failed at the connection to the floor slab. At the top of the donor panel, 140 of the vertical bars failed in tension. However, for the acceptor panels, no gaps were observed between the panels and the roof and floor slabs for Wall 1 through 3 [8].

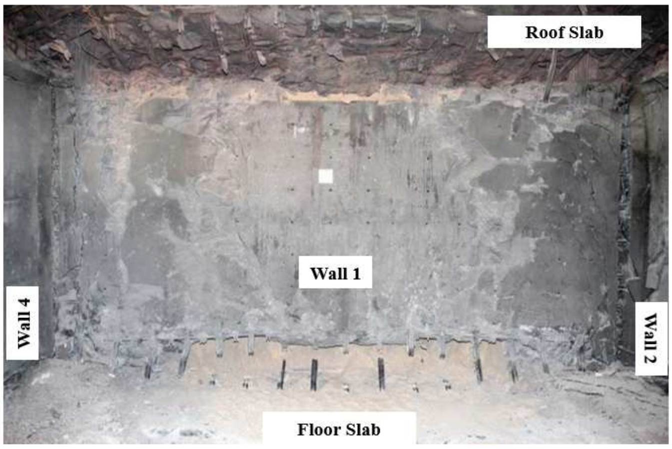
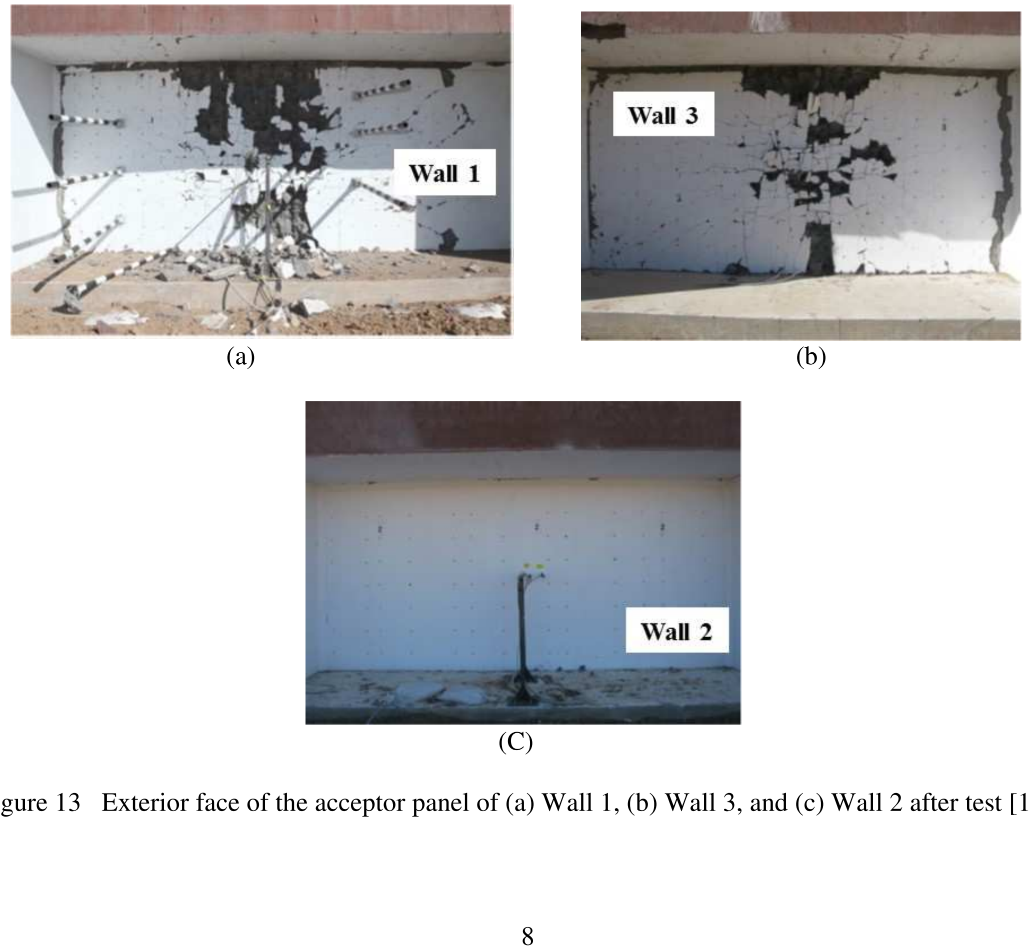


Figure 12 Interior face of the donor panel of Wall 1 after test [8]

From the external of the test structure, Figure 13(a) shows significant spalling and cracking on the non-loaded face of the acceptor panel of Wall 1. Most of the spalling occurred along the vertical centreline of the panel with more spalling occurring at the top of the panel. Similar spall damage was also observed for Wall 3 acceptor panel (see Figure 13(b)). For both walls, the depth of spall extended to the steel reinforcement bars located closest to the non-loaded face of the panel. On the other hand, no spall damage was observed for Wall 2 as shown in Figure 13(c). Spall debris from Walls 1 and 3 was collected after the test. For each wall, the debris collection area extended approximately 1.5 m from the exterior face of the acceptor panel. Debris with a mass exceeding 50 grams were individually weighed and counted. For Wall 1, 357 individual pieces of debris were collected with a total mass of 171 kg and an average mass of 0.48 kg. For Wall 3, 245 individual pieces of debris were collected with a total mass of 115 kg and an average mass of 0.47 kg [8]. As shown in Figure 10, the debris from Wall 1 and 3 are found to be within 30.5 m from the exterior faces of the test structure. In actual implementation, fibre-reinforced plastic (FRP) mats can be applied on the exterior face of the acceptor panels to arrest the spall debris and create a safer environment in the adjacent storage cells.



(a) (b)

(C)

Figure 13 Exterior face of the acceptor panel of (a) Wall 1, (b) Wall 3, and (c) Wall 2 after test [10]

Displacement histories were recorded using LVDTs and accelerometers on the exterior face of the acceptor panels of Wall 1, 2 and 3 in the test. A summary of these results is presented in Table 2. The LVDTs measured the displacement directly while the displacement-time histories were derived from the accelerometer recordings. As shown in Table 2, both measurements were in good agreement. From the results, Wall 1 with the smallest scaled stand-off distance of 0.153 m/kg$^{1/3}$ from the explosive charges, experienced a peak support rotation of 8.4 degrees, which is within the design limit of 12 degrees set for the BRWs. The peak support rotation of 2 degrees for Wall 2 is also consistent with the no spall damage observed for Wall 2.

Table 2 Summary of peak displacement measurements from the acceptor panels of Wall 1, 2 and 3 [7]

Instrumentation	**Wall 1**		**Wall 2**		**Wall 3**	
	Displacement (mm)	Support Rotation (degrees)	Displacement (mm)	Support Rotation (degrees)	Displacement (mm)	Support Rotation (degrees)
LVDT	185	8.4	43	2.0	137	6.3
Accelerometer	181	8.2	34	1.6	Not installed	--

Proposed Explosive Safety Siting

This section will detail how to predict the IBD for a single storage cell of the PUGSS. Recommendations in this section shall only be used with the following restrictions:

1. The loading density or “charge weight to chamber volume ratio” does not exceed 9.23 kg/m$^{1/3}$.
2. The total NEQ does not exceed 5,000 kg.
3. The scaled vent areas ($A/V_E^{2/3}$) of the two openings of the transport aisle are equal and does not exceed 0.29, where A is the area (m^2) for one of the openings of the transport aisle and V_E (m^3) is the total internal volume of the storage cell and the transport aisle.
4. The minimum scaled cover of the storage cell is $0.1Q^{1/3}$, where Q is the NEQ in kg, and the roof slab is designed not to breach.
5. An effective barricade shall be located within 10 to 20 m from the transport aisle opening and constructed to comply with Part III of AASTP-1 on Underground Explosives Storage [9].

Based on the results and observations from the scaled explosive validation test, the following effects, peculiar to a single storage cell of the PUGSS, shall be taken into consideration for quantity-distance purposes:

a) External blast from openings of the transport aisle.
b) External debris from openings of the transport aisle.
c) External debris from the roof.

External Blast from openings of the transport aisle

Based on the descriptions of containment type structures given in UFC 3-340-02, the blast pressure was determined to be a strong function of the scaled vent area ($A/V_E^{2/3}$) and the scaled distance, and a very weak function of the “charge weight to chamber volume ratio” (Q/V) which can be ignored with negligible error. For the same scale distance, the blast pressure decreases with decreasing scaled vent area ($A/V_E^{2/3}$). From the pressure measurements from the explosive test, it is proposed that the following equation be used to predict the IBD (in metres) for external blast pressure at 5kPa for PUGSS storage cell:

$$\text{IBD (5kPa)} = 16.5 * Q^{1/3} \qquad \text{(Eq. 1)}$$

where Q: Net Explosives Quantity (NEQ) in kg

For a PUGSS storage cell with a scaled vent area ($A/V_E^{2/3}$) of the transport aisle opening smaller than 0.29, Eq. 1 will yield a conservative result. Currently, there is insufficient data or analytical work done to determine the detailed relationship between the blast pressure and the scaled vent area and scaled distance. However, this will be addressed in future works.

External debris from openings of the transport aisle

It is noted that the explosive test was conducted with bare C4 charges. In actual storage condition, cased ammunitions might be stored, and this will produce a significant amount of fragments and debris that are likely to exit from the openings of the transport aisle. To reduce the debris throw distance from the transport aisle openings, an effective barricade as prescribed in Part III of AASTP-1 on Underground Explosives Storage can be used (see Figure 14). The maximum range $R_{o\ max}$ (in metres) of the IBD contour line is given by:

$$R_{o\ max} = 0.4*[(-4.025-A)/B] \qquad \text{(Eq. 2)}$$

where $A = -5.25 + \ln(Q)$
$B = -0.0085 - 0.25/(\sqrt{Q})$
Q: Net Explosives Quantity (NEQ) in kg

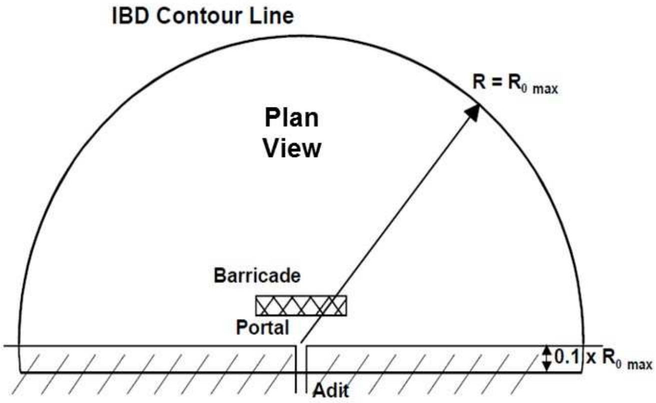


Figure 14 Influence of an effective barricade at the portal entrance of an underground ammunition storage [9]

External debris from the roof

From the scaled explosive test, it was observed that the concrete roof slab directly above the storage was fractured and rubblised. However, the concrete rubble was retained in place by the steel reinforcing in the roof slab. It was also observed from high speed video footages that the soil cover above the concrete was launched with a maximum velocity of 21.3 m/s. The proposed IBD for debris throw from the roof of the PUGSS storage cell can be calculated using the following equation from Part III of AASTP-1 on Underground Explosives Storage:

$$\text{IBD (Roof Debris)} = 38.7 * Q^{1/3} * f_y * f_c \qquad \text{(Eq. 3)}$$

where $f_y = [(Q/V)/1600]^{0.35}$
$f_c = 0.45 + [2.5*(C/Q^{1/3})] - [2.11*(C/Q^{1/3})^2]$
Q: Net Explosives Quantity (NEQ) in kg
V: Chamber Volume in m^3
C: Overburden, Cover in m (assume $C/Q^{1/3} = 0.1\ m/kg^{1/3}$ for conservativeness)

Comparison with a Conventional Aboveground Ammunition Storage Magazine

The IBDs for the different explosion effects of a conventional unbarricaded aboveground magazine and PUGSS storage cell are presented in Table 2. For a NEQ of up to 5,000kg, the IBD of the conventional aboveground magazine is governed by the debris throw distance of 400m, whereas for the PUGSS storage cell, its IBD is governed by the 5kPa air blast distance of 285m. In terms of sterilised land for explosive safety, the savings in land area is approximately 50% ($502,655m^2$ versus $255,176m^2$).

Table 3 Comparison of IBDs between a conventional aboveground magazine and PUGSS storage cell

Explosion Effects	**IBD for Conventional Aboveground Magazine (unbarricaded)**		**Explosion Effects**	**IBD for PUGSS Storage Cell**	
	Q = 750kg	Q = 5,000kg		Q = 750kg	Q = 5,000kg
Air Blast	205m	380m	Air Blast	150m	285m
Debris Throw	400m	400m	Debris from Openings	125m	245m
			Debris from Roof	40m	75m

Alternate Configurations of the PUGSS

After validating the design methodology and response of the BRWs, and determining the explosives safety siting distances for blast pressure and debris throw for a single PUGSS storage cell, this section will briefly discuss the alternative configurations of the PUGSS. Figure 2(a) shows the original concept of PUGSS, which is similar to the Singapore HPM and consists of a series of storage cells separated by BRWs. However, this concept will require every storage cell of the PUGSS to be equipped with a high capacity blast door (of 4 MPa load resistance) for its 6 m wide by 3.5 m high opening. The blast door is required to prevent sympathetic detonation in the event of an accidental explosion in the adjacent storage cell of the PUGSS. Furthermore, it is envisaged that the entire stock of ammunitions stored along the same transport aisle will be lost due to the accidental explosion.

Figure 15 presents the alternative configurations of the PUGSS which storage cells are not connected in series and do share the same transport aisle, thereby removing the need for high capacity blast doors for the large openings of the storage cells. These alternate configurations limit the loss of ammunition stock to only one storage cell, and allow for overlapping of the explosion hazards circles to reduce land sterilisation.

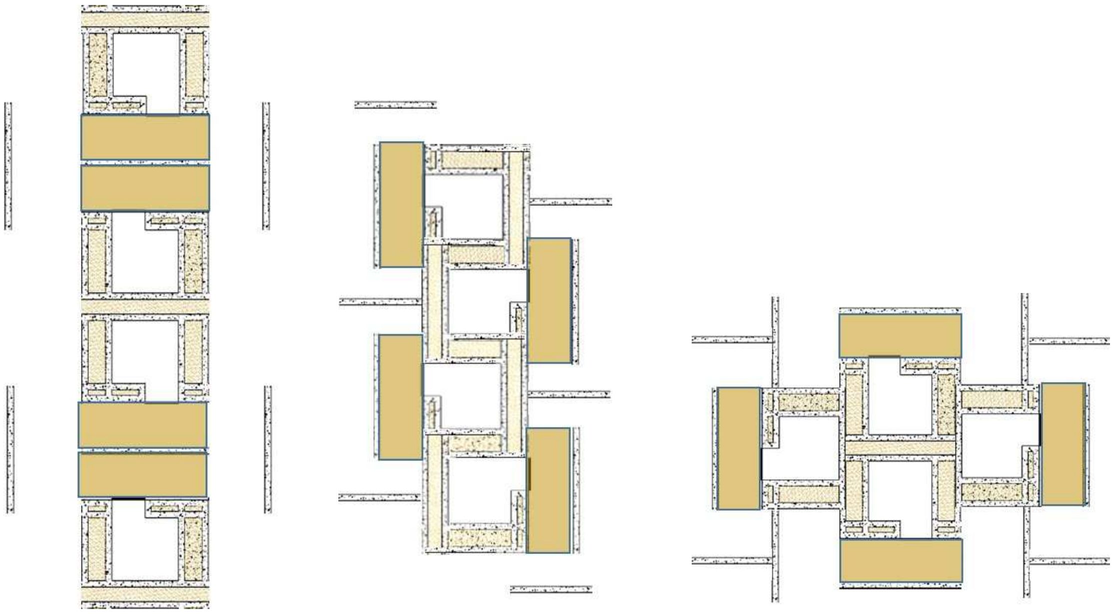


Figure 15 Alternate configurations of the PUGSS

Conclusion

DSTA had collaborated with NAVFAC EXWC to successfully design and develop the BRW technology and PUGSS to reduce encumbered land for ammunition storage when using conventional aboveground magazines. PUGSS is a specially engineered containment structure with BRWs and a hardened roof that are capable of withstanding the internal explosion effects of ammunitions stored within. Based on UFC 3-340-01 and 3-340-02, the BRWs are designed to mitigate blast pressure and primary and secondary fragments, and limit the MCE of an accidental explosion in the PUGSS to only one storage cell. PUGSS has also raised the practical limit of the design loading density of an engineered RC containment structure from 2.4 kg/m^3 to 9.23 kg/m^3.

Starting with the principles behind the BRW design, this paper has delved into the systematic process of developing the PUGSS storage cell which design has been validated through an explosive test of a half-scale structure. IBD equations based on the descriptions of containment type structures in UFC 3-340-02 and Part III of AASTP-1 on Underground Explosives Storage were then proposed for the explosive safety siting of the PUGSS storage cell. For the maximum storage of 5,000kg NEQ, a 50% saving in sterilised land can be achieved by the PUGSS storage cell when compared with a conventional aboveground magazine of the same NEQ. Different configurations of the PUGSS was also presented. DSTA aims to finally incorporate the results and findings of this research and development work on the BRW technology and PUGSS into existing explosives safety standards and guidelines, such as the Allied Ammunition Storage and Transport Publications.

Acknowledgements

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Figures and Tables