Safe Disposal of World War II (WWII) Relic in Upper Bukit Timah

The author(s) provides his/her interpretations and analysis on how the disposal of World War II (WWII) Relic found in Upper Bukit Timah were safely carried out by Singapore Armed Force (SAF) Explosive Ordnance Disposal (EOD) based on the public available information, including the bomb characteristics, disposal methods and safety measures.

Introduction

On 20 September 2023, a war relic was discovered at a construction site along Upper Bukit Timah Road during excavation works. The unexploded ordnance (UXO), WWII 100 kg high explosive aerial bomb, referred as the Japanese Type 94 Aircraft Bomb, has a total weight of 99.79 kg with a charge-to-weight ratio of 42.5%. It is filled with picric acid (TNP), a more powerful explosive than Trinitrotoluene (TNT), resulting in an equivalent of 49.62 kg TNT_{NEQ}.

Due to safety concerns, UXO was deemed too hazardous to relocate and had to be destroyed in place. Detonating such explosives poses potential hazards, with the most significant being blast overpressure, air blast, and fragmentation. Despite their localized effects, they can have significant consequences if not properly managed.

Disposal Approach

Open detonation (OD) was chosen for the UXO disposal operation. It is widely regarded as one of the simplest and safest methods for disposing of unsafe UXOs with small quantities of ammunition (less than 1,000 tonnes). OD helps minimize explosive hazards for both the public and response personnel.

Challenges in treating UXOs with open detonation include the need for large operational spaces to maintain safety distance requirements and the generation of excessive noise during detonations.

Protection against the effects and hazards associated with blast and high-speed fragments during open detonation is achieved through the combination of adequate Quantity Distances (QDs) and the use of physical safety materials as effective barricades.

Low-order detonation was employed. This involves an incomplete or lower-velocity complete detonation, which promotes deflagration over explosion, reducing blast overpressure. This process results in the release of pressure waves and subsequent fragmentation.

In the initial detonation, open detonation treatment involved exploding donor explosives (shaped charges) placed adjacent to the bomb. This method allows the destruction of UXOs without the need for special equipment. The shaped charge injected burning reactive liner material into the bomb, leading to localized burning and cracking. The explosive underwent deflagration, rapidly generating gases. The pressure within the bomb gradually increased due to the inability of the combustion gases to escape, causing the bomb case to rupture before transitioning to full detonation. Any remaining explosive residues were disposed of in a second detonation.

<u>Effects of Explosion and Safety Measures</u>

i. Fragment

Fragmentation occurs when the casing in direct contact with the high explosives is dispersed and shattered upon explosion, sending fragments in all directions. Casualties and damage are more likely to be caused by these fragments, which are typically small and can travel at initial velocities of up to 2000 m/s during detonation.

The "danger area" or impact area due to fragmentation depends on the maximum range of fragments. For a 100 kg WWII bomb, this area is estimated to extend up to 1366 m from the explosive. Individuals, property, and equipment within this range are at risk unless adequately protected, as no more than one fragment would be expected to fly beyond this distance.

To mitigate fragmentation risks, the bomb was detonated within a trench with a depth of 2 m from the surface. Concrete blocks and sandbags were used as barricades, effectively reducing the size of exclusion zones required for safe open detonation operations and minimizing local disruptions. Concrete blocks were positioned at a higher angle (40°) to intercept high-velocity fragments and were estimated to have a ground-level height ranging from 1.5 to 3.0 m, with a minimum thickness of 1500 mm. When subjected to blast, these barricades made of concrete blocks remained substantially intact and effectively intercepted fragments.

Sandbags were used to reduce the distance over which blast and fragmentation traveled, providing protection to personnel, equipment, and property up to a maximum distance of 60 m. For explosives placed at a distance greater than 750 mm below the surface, 20 sandbags per 1 kg of Net Explosive Quantity (NEQ) were required, resulting in the use of 10 layers or 1000 sandbags as an overhead shelter over the trench. A standard sandbag measured 60 cm x 30 cm and contained at least 5 kg of soil or sand, ensuring that it was not filled with materials that could be projected as fragmentation.

ii. Blast Wave

Air blast can cause injury or damage to persons standing unprotected and reasonably close to the detonation. To safeguard against this, 1 ton or 55 concrete blocks were used as barricades to withstand the direct blast load from the bomb. The reflected pressure on the inner faces of the blocks redirected upwards, offering adequate protection to personnel and nearby structures, achieving approximately a 50% reduction in overpressure on the surrounding surface area shielded by the barricade.

Maintaining distance is a critical protection approach against the shock front and overpressure wave produced by the detonation of an explosive. A minimum separation distance of 163.16 m between the explosive and vulnerable buildings inhabited by civilians (such as schools, apartments, multi-story offices, etc.) was required. This distance was determined according to the recommended coefficient of Quantity Distances (QD = 44.4), where QD is calculated using the formula QD = DQ / $Q^{1/3}$, with DQ representing the distance in meters and Q being the Net Explosive Quantity (NEQ) in kilograms. At this distance, the peak Incident (side-on) blast overpressure was predicted to be in the range of 2.0 – 3.0 kPa.

Possible injuries could result from the impact on passersby of failing, broken, or detached panel or window materials. However, personnel exposure was minimized by evacuating residents within a 200 m radius of the unexploded bomb before the detonation.

Buildings not specifically designed to resist blast loading are likely to suffer superficial damage to large panes of glass and lightweight cladding materials. For example, in the case of the Hazel Park, Block 154 Gangsa Road, and other buildings within a 200 m radius of the bomb, inspections were conducted by a team of Building and Construction Authority (BCA) engineers both before and after the controlled explosions of the 100 kg WWII relic. The assessments found these structures to be structurally safe without structural cracks. The BCA emphasized that buildings in Singapore are structurally designed to withstand tremors, including the effects of a blast from a distance.

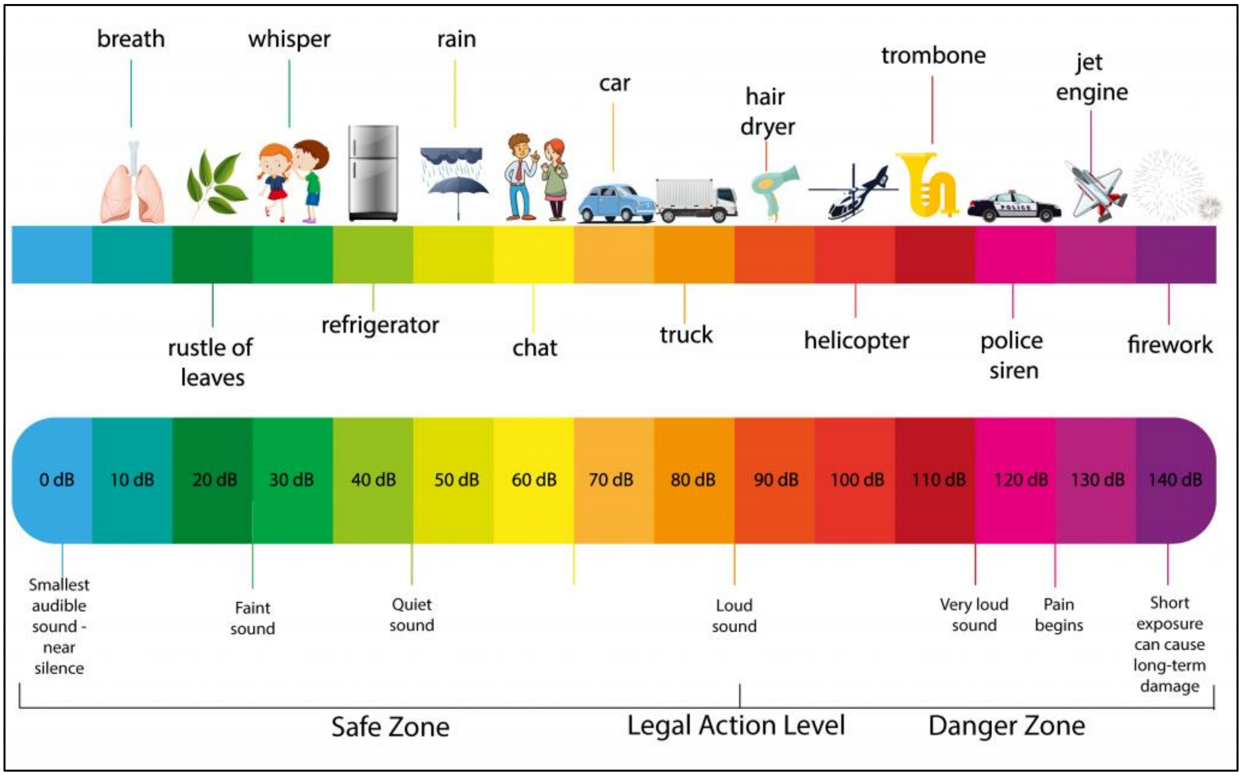
The potential consequences of explosions at various distances, such as damage to brick structures and windows, were tabulated in tables below to provide scientific evidence of the hazards or risks to individuals and property from direct blast effects.

Damage to Windows of 4mm Thick Annealed Glass	Required distance for no damage (m)
Small Window 0.55 m (W) x 0.55 m (H)	95.54
Medium Window 1.25m (W) x 0.55 m (H)	154.34
Large Window 1.25m (W) x 1.55m (H)	345.42

Damage to Brick Structures	Distance
Houses completely demolished	4.41 m
Houses badly damaged, beyond repair, require demolition	6.52 m
Houses rendered uninhabitable, can be repaired with extensive work	11.39 m
Houses rendered uninhabitable, can be repaired reasonably quickly	19.57 m
Houses require repairs, serious inconvenience but remain habitable	39.14 m

iii. Noise

Noise generated by an explosion is also a personnel safety concern. It can cause ear damage at close range and be a nuisance at greater distances. The Health and Safety Executive (HSE) strongly recommends that the C-weighted peak impact or explosive sound pressure level should not exceed 140 dB. This aligns with the Workplace Safety and Health (Noise) Regulations 2011, which specify that the maximum daily exposure duration for sound levels between 130 to 140 dB(A) should not exceed 1 second. Therefore, the 140 dB level serves as a widely accepted "safety cutoff" for exposure to impulsive noises while using hearing protection.



(Source of Image: https://www.plant-tours.com/blog/how-to-choose-communication-headsets-for-events/)

To predict the distance at which a sound level of 140 dB could be achieved, the equation D = 215 $(M_{exp})^{1/3}$ was utilized, where D represents the distance in meters and M_{exp} is the mass of explosive in kilograms. For a Net Explosive Quantity of 49.62 kg TNT, the noise prediction range to achieve a sound level of 140 dB was calculated as 790.05 m.

The Sadovsky formula for the blast wave resulting from a TNT explosion in open air, at standard atmospheric pressure (1 atm) and standard air temperature, was employed to calculate the sound produced by the explosion:

The increase in pressure in atmosphere = $\Delta p_1 = 0{,}84\frac{\sqrt[3]{m}}{r} + 2{,}7\frac{\sqrt[3]{m^2}}{r^2} + 7{,}0\frac{m}{r^3}$

This formula accounts for the increase in pressure in the atmosphere, with ΔP1 is calculated as 0.016649 atm or 1689.916 Pa. The reference sound pressure for 0 dB (the threshold for human hearing) to be 20 µPa. Converting this to decibels (dB) from pascals (Pa) using the formula Db = 20*log(P/P_{ref}), it results in a sound level of 158.5 dB. This explains why the sound from the explosion could still be heard by members of the public beyond a 200 m radius.

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