A STUDY OF THE DAMAGING EFFECTS OF ACOUSTIC SHOCK WAVES FROM A "CONTROLLED" EXPLOSION ON NEARBY BUILDINGS

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1 INTRODUCTION

On 23rd May 2019, an unexploded World War II era bomb was discovered on a building site in Kingston-upon-Thames, approximately just 50 metres away from the back of Kingston University's Penrhyn Road campus. The bomb was believed to contain around 250kg of high explosive material, resulting in Police evacuating the University campus, and all homes in a radius of 400m of the bomb, temporarily displacing approximately 3000 residents. A bomb disposal team from the Royal Engineers' Carver Barracks came the site, packing around 350 tonnes of sand around the bomb, before performing a controlled explosion around 4:15pm on 24th May. Local residents described this as a "very loud blast and reverberations were felt", adding "All the birds flew out the trees, followed by loud cheers and celebrations heard afterward!". The blast was heard as far away as New Malden, some 2.5km (2.2 miles) away. This was despite the bomb – a type commonly dropped by Junkers Ju 87 "Stuka" diver bombers – not being one of the heaviest or most powerful conventional bombs used either in World War II or more recently.

A spokesperson for the Metropolitan police was quoted as saying "So far, limited damage has been discovered with a 50 metre radius of the detonation." However, several cars were damaged on the adjacent Fassett Road and in the nearby car park of Kingston University, and quite a number of windows were broken in houses on Fassett Road. After they event, we logged the pattern of damage to houses and University buildings, finding an interesting pattern of damaged and undamaged houses, indicative of blast waves undergoing multiple specular reflections off plane walls on alternate sides of the road.

In this paper we make a more detailed analysis of that pattern of damage. The event was unusual, being a substantial but controlled explosion in a residential area and consequentially our findings could be of significant value for predicting likely damage from unplanned explosions in similar residential areas. In this paper, we describe our analysis and propose an explanation of what we observe. There is believed to be much unexploded ordinance (UXO) buried near surface level at many locations around the World, from conflicts as long ago as World War I to very recent ones such as Iraq and Afghanistan, and many of that UXO will be in inhabited or cultivated areas. Additionally, uncontrolled accidental explosions, such as the one in the ammonium nitrate store in Beirut in early August 2020, illustrate what catastrophic damage can result from explosions. Our analysis of what occurred in the situation of a "controlled" explosion could provide useful guidance for predicting and mitigating against the damage from other scenarios.

2 RELATED PREVIOUS WORK

2.1 Historical and Prehistorical Background

Naturally-occurring explosions are believed to have caused radical changes on Earth long before recorded history. An asteroid or comet exploding in what is now the Gulf of Mexico around 65 million years ago is widely believed to have triggered the extinction of the dinosaurs whilst, more recently, the explosive and destructive eruption of a volcano comprising much of the Greek island of Santorini (or Thera) around 1500-1600 BCE is believed to have had consequences, including a tsunami and heavy dust clouds, which initiated the decline and eventual collapse of the Minoan Bronze Age civilization on and around Crete (Antonopoulos 1992). In the historical fairly recent past, the explosive eruption of Krakatoa (or Krakatau) in modern Indonesia in 1883 was both devastating and well-documented (e.g. Verbeek 1884, Symons 1888, Thornton 1997), and generated sounds estimated at about 310 dB at source – loud enough to be heard in Perth, Western Australia (3 110 km away) and the Indian Ocean island of Rodrigues near Mauritius (4 800 km away) - plus a supersonic pressure wave, tsunamis and dust clouds which temporarily affected climatic conditions around the World.

Man-made explosions have been common at least since the invention of gunpowder in the Middle Ages, and many have had unintended consequences. In 1687, an explosion of an ammunition store caused major damage to the Parthenon in Athens. During the British-American part of the Napoleonic Wars, a magazine including 300 barrels (estimated to contain a total of 14 000 kg) of gunpowder was detonated by British forces at Fort York in modern-day Toronto, Canada, causing debris to be projected over 450 metres and the sound waves produced deafened many of the nearby United States soldiers, in addition to killing 38 (including their commanding officer) and injuring 222 (Malcolmson 2008). During World War I, the explosion of mines detonated under German lines during the Battle of Messines (Mesen, Belgium) in 1917, involving 455 tonnes of explosives, were believed to have killed around 10 000 German troops (Passingham 2004), with the blast being heard in London (around 250 km away) and allegedly even in Dublin (over 750 km distant) ! The largest single deliberate conventional (non-nuclear) explosion of all time is believed to be the British detonation in 1947 of between 4000 and 7000 tonnes of unused World War II Nazi ammunition on the island of Heligoland in the North Sea off the West German coast. The residents of Hamburg, around 150 km away, were warned to leave doors and windows open to avoid them being shattered by the blast (Connolly 2017). The shockwave was felt some 70 km from the explosion, and even altered the geographical shape of the island (Willmore 1947) and the blast was allegedly heard as far away as Sicily (approximately 1900 km away) ! In contrast, the August 2020 Beirut explosion, which involved around 2700 tonnes of ammonium nitrate – estimated to be equivalent to between 1000 tonnes and 3 400 tonnes of TNT – was heard in Cyprus approximately 250 km away.

2.2 Related Studies

Cullis (2001) performed a set of detailed numerical calculations based on a Eulerian model of a compressible fluid to simulate how blast waves interact with one of two nearby structures. He noted that the reaction of the structures depended on the structures natural resonant frequencies of vibration. Smith and Rose (2005) performed experiments using a model layout of roads and buildings, investigating the pressure changes over time at various points on their road network, and compared these result with those predicted by their own numerical models. Fouchier et al (2017) carried out a laboratory analogue experimental investigation to simulate the effects of a blast wave occurring an urban environment, studying the effects of reflections of blast waves off model buildings in a controlled, laboratory environment.

According to Lehman (no date), typical window glass in good condition will fail at stresses between 55 MPa and 138 MPa. However, other factors including wear and tear, impurities in the materials, environmental conditions such as humidity and the presence of scratches or micro-cracks (which can be created by natural agents such as wind-borne dust) can all seriously reduce the failing stress of glass windows. If the breaking stress of window glass in dry air is 55 MPa, it can be reduced to as little as 43 MPa in adverse conditions, such as a very high level of humidity (Min'ko & Nartsev 2013). The buildings affected by the blast in our scenario are all relatively old so, in some cases, the glass in some of the windows could be quite old and have been subjected to substantial wear and tear, resulting in their breaking stresses being relatively low.

3 RESULTS AND DISCUSSION

The precise location of the bomb immediately prior to detonation was kindly provided by DSTL, using information provided by 33 Regiment Royal Engineers (Explosive Ordinance Disposal) from Carver Barracks, Essex, who carried out the controlled detonation of the bomb. A detail from an Ordinance Survey map of the area, with the position of the bomb marked, is given in Figure 1, and our own photograph of the North side of the location – by then the building site on the right hand side of the photograph – illustrating several boarded-up windows which had been damaged by the blast is shown in Figure 2. The position of the bomb immediately prior to its detonation was just a little forward (West) and South of the blue crane which is clearly visible in the photograph.

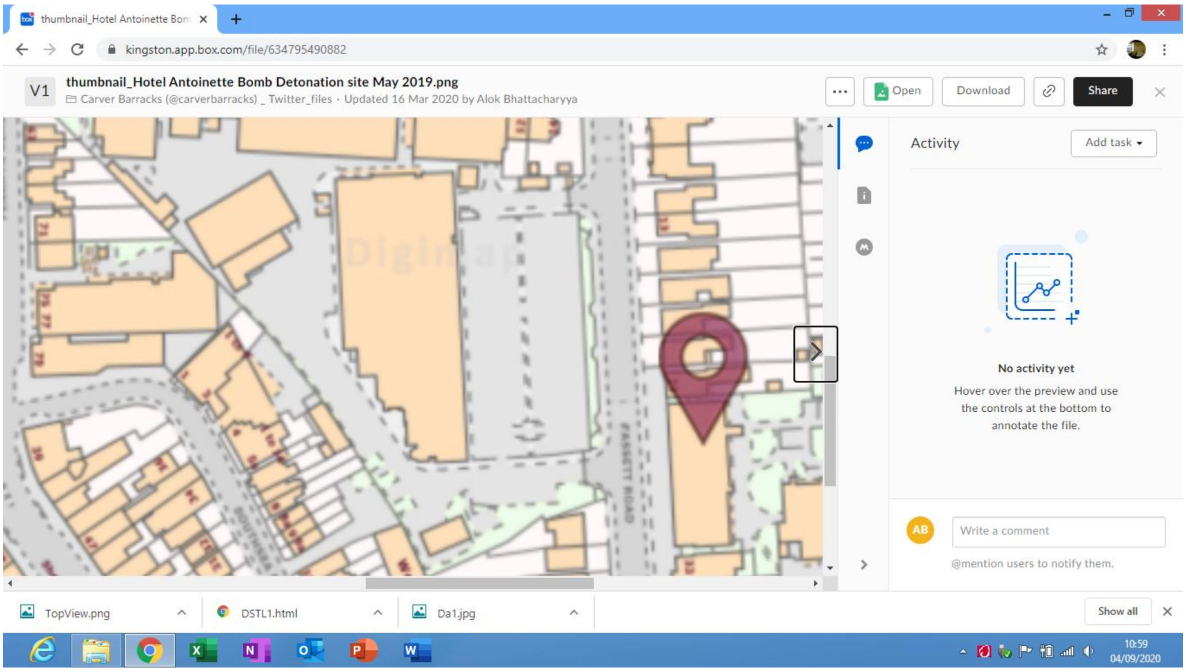

Figure 1 : Detail from Ordinance Survey map of the area, with the site of bomb marked. North is at the top of the map. The bomb's position was, at the date of the map being made, covered by a building of the then Antoinette Hotel. Those buildings were demolished during the early Spring of 2019 and, at the time of the bomb's discovery in late May 2019, was a construction site for a new housing development. The large, unusually shaped building almost opposite, but slightly to the North-West, is the four floor Sopwith Building of Kingston University, of which the long flat East wall is clearly visible on the map.

Moving North along the road from the position where the bomb was detonated, it was observed that first building had no damaged windows. The second building had its top left and top middle windows on the first floor damaged (see Figure 2). The third building showed no damage, but the fourth building had damaged windows on the first floor and damaged windows or doors on the ground floor. The fifth and sixth buildings showed no damage as far the glass doors and windows were concerned. The seventh building showed damage to windows on the ground floor, on the left side of the first floor and to the attic window. This pattern of damaged and undamaged buildings cannot easily be explained in terms of direct "line of sight" shockwaves – they are blocked from direct line of sight from the point of the explosion by the fabric of the buildings themselves - but is instead analysed in terms of multiple specular reflections off the walls of the buildings on either side of the road (see Figure 3). In contrast, to the South of the bomb's position, only buildings to the in direct "line of sight" of the detonation position showed any obvious damage. On the South side, no long plane walls were present to allow the multiple specular reflections of the shock ways which were observed to the North of the point of detonation. It should be noted that all windows in the University's Sopwith building to the West (right hand side of map images) were opened prior to the bomb being detonated, to mitigate against the effects of the shock wave from the explosion.

Figure 2 : Photograph of the area of the bomb site, taken a few days after the detonation, showing boarded-up windows which had been damaged as a consequence of the bomb's detonation on houses on Fassett Road, immediately to the North of the bomb's position (close to the blue crane on the right of the photograph). The pattern of damaged and undamaged windows is discussed below. Very few windows in houses to the South of the bomb's position were damaged, and those which were damaged on that side were all in direct "line of sight" from the point of explosion.

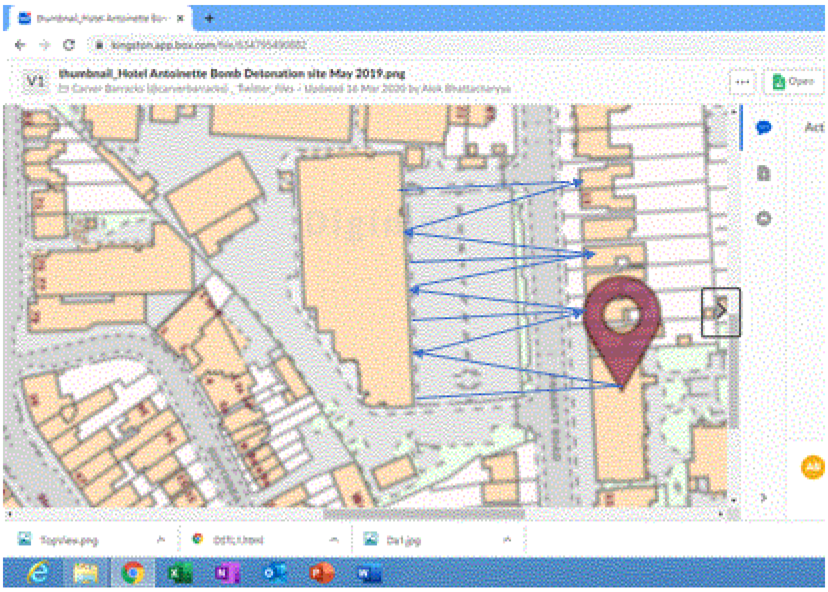

Figure 3 : Enlarged detail from same Ordinance Survey map as Figure 1, with North at the top, showing the bomb detonation position and specular reflections off the plane flat walls of the nearby buildings, notably the Sopwith Building of Kingston University to the West (left) of the road, explaining the locations of the damaged and undamaged windows on the right (East) side of the road.

Although some previous research has indicated that reflections of blast wave from plane solid surfaces may not be strictly specular at high angles of incidence greater than about 40º (Cullis 2001), the analysis below only requires small incidence angles (up to around 30º), so our assumption of purely specular reflections is likely to be valid, at least to a good approximation.

All the necessary lines in the image (Figure 3) were added to show a "Geometrical Acoustics" ray diagram of possible multiple specular reflections of shock waves produced by the detonation. Perpendicular lines were drawn first between the approximate midpoint of each of the damaged portions of each damaged building and the corresponding nearest point on the large plane East wall of the University's Sopwith Building (the large, unusually-shaped one just to the West, or left, of Fassett Road). There are three such perpendicular lines shown. Another such line was from the given location of the point of detonation of the bomb to the nearest point on the East wall of the Sopwith Building. The rays were drawn from the source and assumed to have been specularly reflected back and forth between the Sopwith Building and the damaged buildings on the East (right hand) side of Fassett Road. This model provides a plausible explanation of the pattern of damage observed, without requiring more complicated considerations such as diffraction or interference of waves.

Whilst some amateur video footage of the explosion has been posted on-line, no official aerial view footage of the detonation is available in the public domain. However, aerial view video of a similar controlled detonation of a similar bomb in Aston, Birmingham, UK, in 2017 by the Royal Engineers is available for view at https://www.rt.com/uk/388655-drone-video-bomb-explosion/ (last accessed 7 September 2020). In that video of the Birmingham explosion, the asymmetrical nature of both the initial blast and the subsequent dispersion of the resulting debris is quite noteworthy. In part, this is due to the wall of the building on the right of the video frame. However, the lack of dispersion of debris "up" and "down" the image frame, compared to the large amount initial leftward and rightward motion, is quite marked. The dominance of the motion to the left may indicate a right to left blowing wind, but the text of the on-line article indicates that the site of the bomb was close to quite a large "amount of sensitive infrastructure in the area, particularly the A38 Aston Expressway flyover and a gas pipe". It is probable that the Engineers packed a large amount of the 250 tonnes of sand used in that case in a manner to particularly protect those items of sensitive infrastructure, resulting in an asymmetrical blast wave. It is probable that this was also the case in the situation of the Kingston 2019 controlled detonation.

The "geometrical ray tracing" approach could also explain why the damage was spread over a wider area in the houses further from the explosion. $(\theta - \phi)$ and $(\theta + \phi)$. If these undergo a single specular reflection, then the angles of reflection would also range between $(\theta - \phi)$ and $(\theta + \phi)$, producing a "reflected continuation" of the cone. This would continue with each subsequent reflection, so that the energy from the explosion was spread over a wider area on each reflection. Eventually, due to some energy being absorbed by the reflecting surface on each reflection, as well as the remaining reflected energy being spread over a wider area, the later reflections will be too weak to cause any significant damage such as breaking windows. However, this could explain why the damage caused by the second and third reflections was more widespread (in terms of area damaged) that that of the first reflection. South of the detonation site, where there was no long plane wall present to allow the multiple reflections, only windows in direct line of sight of the position of the explosion were damaged.

(a) (b) (c)

Figure 4 : Some photographs, courtesy of the Royal Engineers of Carver Barracks, showing aspects of the site prior to their controlled detonation of the bomb. From left to right : (a) Engineers filling sandbags around the bomb. Kingston University's Sopwith building can be seen in the background. The rubble in the front of the image is left over from the demolition of the buildings of the hotel located there until a few weeks before the photograph was taken, and is not directly related to the bomb explosion. (b) later in the same operation. Sand bags can be observed to be in place on three sides of the bomb at this point. (c) A close-up of the bomb and the detonator which the Engineers had attached to it. Part of a soldier's booted foot can be seen in the bottom left of this photograph, to provide a sense of scale.

4 CONCLUSIONS AND FUTURE WORK

In this analysis of damaged caused by the controlled explosion of the 250kg World War II bomb discovered and detonated in Kingston upon Thames in late May 2019, an actual photograph was used to identify houses with damaged glass windows and doors, and these were located on an Ordinance Survey map of the area that showed the place of detonation and other surrounding buildings. Ray tracing was used following laws of specular reflection to show how pressure wave initiated by detonation could have caused the damage observed in the locations it occurred, and where no damage occurred.

For further work, we would aim to use graphical modelling using 3D Google Earth images to find the required height of the surrounding barrier made of sand bags so that no building in the vicinity falls within the line of sight from the explosion. We would recommend that in future such controlled detonations (i) precautions should be taken to increase the level to which the surrounding sand bags were raised, to avoid any building remaining in the direct line of sight from the point of detonation and (ii) there should not be any gaps left between the sand bags. This should avoid the possibility of the type of specular reflections of the sound energy discussed in our analysis.

5 ACKNOWLEDGEMENTS AND DISCLAIMER

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