A practical method to simulate and analyze the consequence of ammonium nitrate explosion accidents

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Research Article

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Abstract

Several catastrophic ammonium nitrate (AN) explosion accidents have been observed over the last two decades. Previous studies have been mainly focused on investigating adverse effects caused by the AN explosion, while only a few systematically analyzed the consequences and effects of AN blast. The present study collected the data on three ammonium nitrate explosion accidents (accidental explosion of the US fertilizer plant in 2013; an accidental explosion of China's Tianjin port in 2015, and a recent explosion (2020) of the Beirut port in Lebanon) and analyzed the consequences of the accidental explosions through simulation calculation, thus providing a scientific explanation for the AN explosion in media reports. According to the actual damage, it was recommended that the impact of both shock wave overpressure and ground shock on people and buildings should be considered in the accidental explosions. Calculating the shock wave overpressure, ground shock, and the influence distance, and then comparing the calculations with the actual situation can be used as a feasible method in the rapid analysis of the accidental consequences of ammonium nitrate explosion.

1. Introduction

Ammonium nitrate (AN), also known as NH_4NO_3, is a colorless and odorless transparent crystal or white crystal commonly applied as an industrial chemical. Because of its high nitrogen content, high fertilizer efficiency, and low production cost, it is widely used as a high-quality agricultural fertilizer in agricultural production (Yang et al., 2017; Zygmunt and Buczkowski, 2007). AN is stable at room temperature and insensitive to impact, collision or friction. Nevertheless, it is also a kind of oxidizer with combustion supporting characteristics that may cause an explosion if it is not stored (exposed to high temperature, high pressure, oxidant, or spark) and properly transported (Zygmunt and Buczkowski, 2007). Based on these properties, it is also used as an explosive, usually mixed with fuel, known as AN fuel oil (ANFO) (Pittman et al., 2014).

Incidents involving AN have occurred all over the world during all supply train stages including transportation, production, and storage of the material. Over the past decade, many serious AN explosion accidents have been reported, such as the explosion of the US fertilizer plant in 2013 (Laboureur, 2016), the explosion of China's Tianjin port in 2015 (Li et al., 2015), and a recent explosion of the Beirut port in Lebanon (Shakoor et al., 2020). These accidents caused serious damage to the surroundings, leading to significant environmental pollution and adverse social impact. In addition, they led to a large number of casualties and tremendous pressure on the medical system. The urgent task is to manage and control the process risk actively and prospectively by using the method of risk management, on the basis of the comprehensive risk analysis of the process system, in order to prevent the occurrence of major explosion accidents (Chen at al., 2019).

The explosion caused by AN leads to air-blast shockwave and ground shock (Cernak, 2015; Bui et al., 2019). A high-temperature and high-pressure gas that are produced following the explosion rapidly expand, squeezing the surrounding air like a piston, transferring part of the energy released from the explosion reaction to the compressed air layer. The air is disturbed by impact, and the pressure and density of the air tend to suddenly change. In addition, when an explosion occurs on the ground, the ground goes through both air blast-induced and direct-induced ground shocks (Bui et al., 2019). Except for air blast-induced by ground shock, the explosive energy is directly transmitted through the ground and introduces the direct-induced ground motions and cratering-induced ground motions. Therefore, the ground shock can aggravate looseness of buildings, thus potentially causing secondary damage to people.

Over the last couple of years, scientists have been working hard to develop models and methods to predict and analyze the consequences of the explosion. However, most of the current studies have focused on adverse effects caused by the explosion, while only a few systematically analyzed the consequences and effects of the explosion. Thus, in order to effectively deal with the accidental AN explosions and improve the efficiency of disaster rescue, it is urgent to analyze the consequences of such accidental explosion, and establish a rapid prediction and evaluation method to provide guidance for medical rescue and reconstruction.

2. Three An Explosion Accidents

2.1. The explosion accident of the US fertilizer plant

On April 17, 2013, AN explosion occurred in chemical storage and distribution facility in West, Texas, USA. The center of the explosion generated 28.3 meters wide and 3 meters deep crater. The explosion destroyed a middle school, nursing home, numerous residences, and businesses. Fifty structures were significantly damaged, while 100 structures were slightly damaged. In addition, an apartment complex was destroyed (Laboureur, 2016). Debris was found up to 2.5 miles from the plant. Fifteen people died, and 228 people were recovered to the hospital, among whom 46 were admitted. Fifteen people were killed, among whom ten were firefighters, two were civilians who tried to extinguish the fire, and three were civilians who lived in a close-by residential area (Laboureur, 2016). West fertilizer claimed to have in storage 540,000 pounds of AN, 110,000 pounds of anhydrous ammonia, 540 pounds of Grazonnext (herbicide), 60 pounds of Reclaim (herbicide), 192 pounds of Remedy Ultra (herbicide), 29.75 pounds of Surmount (herbicide), and 400 pounds of Yuma (insecticide) (Laboureur, 2016).

2. 2. The explosion accident of China's Tianjin port

On August 12, 2015, an explosion occurred at a container terminal in Tianjin Binhai New Area (Li et al., 2015; 360 baike, 2021). The explosion was caused by flammable and explosive materials inside the container. At the explosion scene, there was a mushroom cloud tens of meters high, accompanied by projective combustion. The center of the explosion generated a very large crater-like hole with a width of 97 meters and 2.7 meters deep. One hundred sixty-five people were killed (including 24 firefighters in active service, 75 firefighters in Tianjin port, 11 police officers, 55 employees, and residents of enterprises where the accident happened and surrounding enterprises), 8 people were gone missing (including 5 firefighters in Tianjin, 3 employees of surrounding enterprises and family members of firefighters in Tianjin Port), 798 people were injured (58 seriously injured and 740 slightly injured), 304 buildings, 12428 commercial vehicles and 7533 containers were damaged (360 baike, 2021). According to reports, 72 kinds of dangerous goods (4840.42 tons) were stored on-site, including 800 tons of AN, 360 tons of sodium cyanide, 48.17 tons of nitrocellulose, nitrocellulose solution, and nitro lacquer (360 baike, 2021).

2. 3. The explosion of the Beirut port in Lebanon

On the afternoon of August 4, 2020, a huge explosion occurred in the port area of the Lebanese capital, Beirut, forming a bucket-shaped crater with a diameter of about 140 meters. At the origin of the explosion epicenter, most of the buildings within 2 km were destroyed. The sound and shock waves were felt in Cyprus, 180 km away. Government officials have confirmed that the two explosions, which occurred in the early evening on Aug 4, after a warehouse caught fire on Beirut's northern industrial waterfront, resulted from the detonation of 2750 tons of AN that has been improperly stored for six years. At least 200 people were killed, and more than 7000 were injured (Landry et al., 2020). The explosion left 300000 people homeless and caused up to $15 billion in damage. Also, 50000 houses, 9 large hospitals, and 178 schools were damaged (Devi, 2020). Due to the strength of the blast, the explosion was considered as one of the largest recorded in modern history (SBS News, 2020).

3. Accident Analysis

3. 1. Explanation of AN explosive phenomenon

Pure AN is relatively stable at room temperature. Yet, when exposed to high temperature, high pressure, oxidizing substances and electric spark, it can explode. High temperatures caused the three explosions mentioned above. When the temperature exceeds 400 degrees Celsius, AN decomposes and explodes. The chemical equation for the explosion of AN is as follows:

$4NH_4NO_3=3N_2+2NO_2+8H_2O$

According to the above chemical equation, the explosion of 270 tons, 800 tons, and 2750 tons of AN produced about 121.6 tons, 360.2 tons and 1238.3 tons of water, 77.6 tons, 230.0 tons and 790.4 tons of nitrogen dioxide, and 70.9 tons, 210.0 tons and 721.8 tons of nitrogen, respectively. Because the molecular weight of water is only 39.1% of nitrogen dioxide, water's kinetic energy is higher, and the propagation distance is farther. However, nitrogen dioxide has little kinetic energy and can only be lifted into the air under the pressure of an explosion's epicenter. This explains why a huge white gas wave was formed during explosions, following a reddish-brown cloud from the explosion center. The first huge white wave was actually a large amount of high-temperature and high-pressure steam produced by AN explosion. It has also been found that the explosion caused by solid or liquid explosives is a condensed phase explosion (Liu, 2016). The condensed phase explosive process is usually initiated by thermal pulse, mechanical pulse, or direct action of detonator or booster. Detonation is usually caused by thermal pulses, after which it goes through an unstable combustion stage (Liu, 2016). It was reported that there were many dangerous chemicals stored in the warehouse in three accidents. The thermal pulse generated by warehouse fire can provide continuous energy for all kinds of condensation hazardous chemicals, thus leading to the intense explosion of condensation explosives. Therefore, it is believed that the three explosions were caused by condensed phase explosives.

3.2. Analysis of crater diameter caused by AN explosion

Based on TNT experiments and previous literature, Ambrosini *et al* validated the empirical equation of Kinney and Graham that relates the diameter of the crater (D) to the TNT mass (Q_{TNT}) for an explosion at ground level and which is expressed below with mass in kg and distance in meters (Ambrosini et al., 2002; Laboureur, 2016). Following this correlation, we calculated the diameter of the crater caused by the explosion of TNT.

$$D = 0.8(Q_{TNT})^{\frac{1}{3}}$$

For other types of explosives, TNT equivalent can be converted according to the following formula.

$$Q = \frac{q_i}{q_{TNT}} Q_i$$

where is the TNT explosive equivalent, kg; is the explosive quantity of certain explosive, kg; is the detonation heat of certain explosive, kJ/kg; is the detonation heat of TNT explosive, kJ/kg.

The detonation heat released by 1kg TNT explosive is 4230 ~ 4836kJ/kg, and the average detonation heat is 4500 kJ/kg generally. AN is calculated with AN explosive as a reference, and the detonation heat of AN explosive is 4000 kJ/kg.

Figure 1 shows the theoretical and actual crater diameters calculated according to explosive equivalents in three accidental explosions, respectively. As shown in Figure 1B, the crater's diameter formed by the 270 ton AN explosion in the USA was 28.3 meters, which is much smaller than the predicted diameter of 49.7 meters (Figure 1A). By comparison, 800 tons of AN explosion in China formed a crater with a diameter of 97 meters (Figure 1A), but the theoretical diameter calculated by the formula was 71.4 meters (Figure 1B), which was slightly smaller than the actual crater diameter. Similarly, the predicted value of a crater with a diameter of 107.8 meters formed by the explosion of 2750 tons of AN in Lebanon was also smaller than the actual diameter of 140 meters (Figure 1). Bull and Woodford pointed out that the crater's deviation can reach 30-40% (Bull and Woodford, 1998). AN has an excellent crater effect, which may lead to underestimation of crater diameter based on TNT mass estimation. Moreover, the AN effectiveness reported in the literature varies from 0.25 or 0.3-0.55, to 0.84 (Laboureur, 2016; Hutchinson and Skinner, 2007). Some studies suggested the use of 0.346 as a standard because it corresponds to the ratio of explosion heat of AN to that of TNT. Therefore, choosing a higher effective factor will make the quality assessment closer to the actual value. Combined with the prediction of crater diameter in these accidental explosions, we speculated that only when the AN mass reaches certain height, a better crater effect will appear, which may result in underestimation of the crater diameter. Based on the above results, we confirmed that the formula should be modified with reference to the empirical validity so as to better predict the actual diameter of the crater caused by an explosion.

3.3. Impact of shock wave overpressure on casualties

AN explosion releases a large number of high-temperature and high-pressure explosion products, which impact the surrounding air at high speed and increase the pressure, density, and temperature, forming air-blast shockwave. According to the Chinese national standard "safety regulations for blasting" (GB6722-2014), the shock wave overpressure is calculated according to the following formula under the condition of flat terrain.

$$\Delta p = 14\frac{Q}{R^3} + 4.3\frac{Q^{\frac{2}{3}}}{R^2} + 1.1\frac{Q^{\frac{1}{3}}}{R}$$

where is the shock wave overpressure, × 10^5 Pa; *R* is the distance between protecting objects and blasting points, m; *Q* is the explosive quantity equivalent to TNT in one blasting, the total quantity is the simultaneous blasting, and the maximum quantity is the delayed blasting, kg. For other types of explosives, TNT equivalent can also be converted according to the above listed formula (2.3).

In Table 1, four levels of casualties caused by shock wave overpressure are defined: mild injury, moderate injury, severe injury, and extremely severe injury. The shock wave overpressure values at different distances from the explosion epicenter can be obtained by formula calculation. Figure 2A shows the overpressure variation trend with the distance of the explosion epicenter for 270 kg, 800 kg, and 2750 kg AN, respectively. It can be seen from the figure that there is a functional relationship between the shock wave overpressure and the charge amount, and the distance from the explosion epicenter. Higher explosive production generates a higher overpressure of the shock wave (Figure 2A). The results also showed that with the increase of the distance from the epicenter, the overpressure values of shock waves produced by different equivalent explosions gradually decreased; nevertheless, after reaching a certain distance (about 1,000 meters), overpressure values of shock waves were significantly reduced (Figure 2A). Therefore, the range and degree of casualties and building damage caused by shock wave overpressure could be calculated theoretically according to the variation of shock wave overpressure in different areas.

Figure 2B showed the predicted zones of casualties caused by shock wave overpressure in the three explosions. The global positioning system (GPS) satellite images and aerial views were collected through an online search. By formula calculation, after the AN explosion, the shock wave overpressure zone of more than 1×10^5 Pa was formed at 215 meters, 309 meters, and 467 meters away from the respective explosion epicenter (Figure 2B). Referring to Table 1, the results showed that within 215 meters, 309 meters, and 467 meters of respective explosion epicenter, high shock wave overpressure would cause death in these areas. Within 215-309 meters, 309-444 meters, and 467-670 meters, the shock wave overpressure was $(0.5\text{-}1)\times10^5$ Pa, which could cause severe internal bruising and even death. In addition, in the zones of 309-417 meters, 444-599 meters, and 670-903 meters, the shock wave overpressure was $(0.3\text{-}0.5)\times10^5$ Pa, which could lead to eardrum injury, moderate contusion, and fracture. However, in the zones of 417-540 meters, 599-776 meters, and 903-1171 meters, the shock wave overpressure was reduced to $(0.2\text{-}0.3)\times10^5$ Pa, which could only cause a slight contusion. Due to the lack of accurate information on casualties in three explosion accidents, this study could not accurately compare the theoretical prediction with the actual casualties. Still, the calculated zones of casualties were basically consistent with the media reports.

3.4. Impact of the shock wave overpressure on buildings

In Table 2, seven damage scales for the severity of the blast-induced damages for buildings are defined: Damage Scale 1 (DS1) almost no damage, Damage Scale 2 (DS2) minor damage, Damage Scale 3 (DS3) mild damage, Damage Scale 4 (DS4) moderate damage, Damage Scale 5 (DS5) severe secondary damage, Damage Scale 6 (DS6) severe damage, and Damage Scale 7 (DS7) complete destruction. Since DS1 and DS2 cause slight damage to buildings, Figure 2C showed only the predictable zones of the other five damage scales (DS3-DS7). These distances represent the boundaries for the zones of the fiver damage scales. It can be seen from the figure that the shock wave overpressure was more than 0.76×10^5 Pa within the range of 247 meters, 355 meters, and 536 meters away from the respective explosion epicenter; buildings within this range were expected to be completely damaged (DS7). In the range of 247-293 meters, 355-422 meters, and 536-636 meters away from the respective explosion epicenter, the explosion overpressure was $(0.55\text{-}0.76)\times10^5$ Pa, and the buildings in this area were seriously damaged (DS6) (Figure 2C). In addition, buildings within 293-351 meters, 422-504 meters, and 636-761 meters away from each explosion epicenter suffered serious secondary damage (DS5); buildings within 351-467 meters, 504-671 meters, and 761-1013 meters moderate damage (DS4), and buildings within 467-963 meters, 671-1384 meters and 1013-2089 meters a slight damage (DS3)(Figure 2C). These results show that buildings within the three explosion epicenters of 963 meters, 1384 meters, and 2089 meters were damaged in different degrees by the shock wave overpressure.

For the calculation of overpressure of blast air shock wave, the commonly used empirical formulas in the early stage are the national standard "safety regulations for blasting" (GB 6722-2014/XG1-2017), Henrych formula, Sadovsky formula, and Brode's formula (Wu and Gao, 2014). Many scholars applied those formulas for calculation, but these empirical formulas were mainly based on the experimental data and theoretical analysis results. Because of the short history of the explosion, the accuracy of experimental results is often affected. With the rapid development of computer technology, numerical simulation methods have been developed for studying explosion effects in recent years. Many scholars have carried out a series of studies on shock wave overpressure by combining explosion tests with numerical simulation. This study collected and sorted out buildings' actual damage through the Internet and literature reports and described the damage with different distances around the explosion epicenter (Table 5-7). These tables provide the comprehensive damage conditions of the buildings in different damage scale zones. The actual damage, the damage degree, and scope caused by the three explosion accidents (USA, China, and Lebanon) were basically consistent with the theoretical prediction. The air blast shockwave from three explosion accidents did contribute to the structural damages of the buildings. Moreover, the predicted range of this formula was in good agreement with the actual damage observed in most buildings. For some buildings, such as building A5 and C2, the severity of the damage was more like the moderate damage scale (DS4). Nevertheless, these buildings were actually located in the DS3 (mild damage) zone (Table 5 and Table 7), which was not consistent with the results. In addition, the damage to building B6 could be almost classified as no damage level (DS1) when the building is actually located in the DS2 (minor damage) zone (Table 6). These phenomena could not be explained by the air-blast incident overpressure.

3.5. Ground shock caused by AN explosion

Although the seismic wave caused by the AN explosion can not destroy the original solid rock, it generates vibration or shaking of all objects on the ground near the explosion source. When the blasting vibration reaches a certain intensity, the buildings (structures) around the blasting area are damaged. According to the national standard "safety regulations for blasting" (GB6722-2014), the safe permissible distance of blasting vibration can be calculated according to the following formula.

$$R = \left(\frac{K}{V}\right)^{\frac{1}{\alpha}} \cdot Q^{\frac{1}{3}}$$

The ground shock can be calculated according to the conversion formula below.

$$V = \frac{K}{\left(\frac{R}{Q^{\frac{1}{3}}}\right)^{\alpha}}$$

where is the ground vibration peak particle velocity (PPV) at the location of the protected object, cm/S; is the distance between the protected object and the blasting point, m; is the explosive quantity, the total quantity is for the simultaneous blasting, and the maximum quantity is for the delayed blasting, kg; and α are the coefficients and attenuation indexes related to the terrain and geological conditions between the blasting point and the calculated protected object. It can be selected according to Table 3 or determined by field test. Considering the geological and topographical conditions of the explosion site, we chose soft rock parameters, k = 350, and α = 1.8.

The relationship between seismic intensity and vibration physical quantity is shown in Table 4. According to the calculation results of the relationship between PPVs and distances, combined with Table 4 and the Chinese Seismic Intensity Scale (GB/T17742-2020), and by taking class III buildings as an example (the explosion affecting civil buildings and the structure was Class III buildings), we calculated and analyzed the impact caused by ground shock. Figure 3 shows that after 270 tons, 800 tons, and 2750 tons of AN explosion, within 187 meters, 269 meters, and 406 meters from each explosion epicenter, respectively, the seismic intensity was more than 10 degrees, and most of the class III buildings were toppled. The PPVs within the range of 187-275 meters, 269-396 meters, and 406-597 meters from each explosion epicenter were equivalent to 9 degrees of seismic intensity, and these areas were severely damaged. In addition, the building structure was severely damaged and partially collapsed. The PPVs generated within a range of 275-405 meters, 396-581 meters, and 597-877 meters from the epicenter of the respective explosions were equivalent to 8 degrees of seismic intensity, and these areas were moderately damaged, and the structure of the building was damaged and would need to be repaired before it could be used. In the range of 405-595m, 581-854 meters, and 877-1615 meters away from each explosion epicenter, the PPVs were equivalent to the seismic intensity of 7 degrees. These areas suffered mild damage, partial house damage or cracking, and required minor repair or no repair at all. Thus, it was concluded that in the three explosion accidents, buildings within 595 meters, 854 meters, and 1615 meters from the respective epicenter of the explosion could suffer varying degrees of damage due to the ground shock caused by the explosion. Results also showed that the ground-shock reduced as the standoff distance increases.

Previous studies have found that buildings' roof collapse may be a typical sign of building damage related to ground shock. In addition, with the increase of the distance between the explosion epicenter and the buildings, the contribution of the ground shock to the structural damage is more obvious. In the explosion in Texas, USA, many local buckling damages were observed on the collapsed roof truss, which can not be explained by the air-blast overpressure (Dai et al., 2016). Their results also showed that in the destructive failure and hazardous failure zones, very few damage characteristics caused by ground shock could be identified. In these zones, the ground shock-induced damages were overwhelmed by the air-blast incident overpressure-induced damages. In the repairable moderate damage zone, the vertical cracks appear. These results suggested that the damage observed on-site could be more accurately explained by considering the influence of ground shock. Thus, it was proved that the AN explosion accident's overpressure was the leading factor of building damage. Although ground shock was a secondary factor, it still plays an important role. In a future analysis of the consequences of such accidents, the influence of air blast overpressure and ground shock should be considered comprehensively so that the relationship between explosion load and building damage could be accurately obtained.

4. Conclusions

In this study, a fast prediction and evaluation method were established and verified based on the analysis of three typical explosion accidents. Combined with the scene situation of explosion accident and prediction analysis, the following conclusions are drawn:

(1) According to the explosives' properties on-site, these accidental explosions were caused by condensed phase explosives. Combined with the blasting site conditions and relevant data, the crater diameter could be calculated by explosive equivalent, but there was a certain deviation between the predicted value and the actual value. Consequently, the formula needs to be further modified.

(2) The severity of casualties and building damage caused by the explosion decreased with the increase of the standoff distances. The farther away the residents and buildings were, the fewer casualties and building damage occurred. These distances could be calculated by the scaling law, which was replaced by the equivalent TNT mass of the explosive and the damage scale's overpressure boundary value. The formula should be suitable for estimating blast-induced damage characteristics and damage scales or severities, and both the air-blast incident overpressure and ground-shock PPV in the field.

(3) Marking damaged areas on the map might be helpful for visualization. Moreover, the air-blast overpressure was typically the dominant factor for casualties and building damages. The ground shock was the secondary factor, but it was still important. Consideration of the ground-shock effects can lead to a more comprehensive and precise explanation of the buildings' field-observed damages.

Based on the above resulting analysis, from the perspective of process safety and risk project, this research can be applied to the following two aspects: first, the AN explosion has a devastating impact on nearby residents, mainly due to the lack of zoning or urban planning to create buffer zones between sites storing explosives and critical infrastructure. Through our mathematical model, we can help government departments to make more effective urban planning and guide the delimitation of "safe distance" and "exclusion zones". Secondly, this method can analyze the consequences of typical AN explosion accidents and predict the severity and influence range of the consequences of explosion accidents more accurately, providing a reliable basis for carrying out emergency rescue in a timely and effective manner.

Declarations

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Tables

Table 1
Relationship between casualties and air-blast overpressure

Overpressure (10^5Pa)	**Injury level**	**Injury situation**
0.2-0.3	Mild	Minor contusion
0.3-0.5	Moderate	Eardrum injury, moderate contusion, fracture, etc.
0.5-1.0	Severe	Severe internal bruising and even death
>1.0	Extremely severe	Death

Table 2
Relationship between damage degree of buildings and air-blast overpressure

Damage scale		DS1	DS2	DS3	DS4	DS5	DS6	DS7
		Almost no damage	**Minor damage**	**Mild damage**	**Moderate damage**	**Secondary severe damage**	**Severe damage**	**Complete destruction**
Overpressure (10^5 Pa)		<0.02	0.02-0.09	0.09-0.25	0.25-0.40	0.40-0.55	0.55-0.76	>0.76
Damage description	Glass	Accidentally damaged	A small portion was broken chunks; most were small	Most pulverized to break into small pieces	Break up	—	—	—
	Wooden doors and windows	No damage	The window sash is slightly damaged	A large number of window sashes are damaged, and doors, windows, and window frames the destruction	The window sash fell or fell inside, and the window frame and door leaf were damaged.	Doors and window sashes are destroyed, and window frames fall	—	—
	Brick facade	No damage	No damage	There are small cracks, the width is less than 5mm, and it is slightly inclined	Large cracks appear, the width of the joint is 5-50mm, obviously inclined, small cracks appear in the brick stack	Large cracks larger than 50mm appear, severely inclined, large cracks appear in the brick stack	Partially collapsed	Most to all collapsed
	Wooden roof	No damage	No damage	The wooden house panel is deformed, occasionally tearing apart	Wooden house roof panels and wooden purlins are demolished, and wooden roof trusses are loose	The wooden purlins are dismantled, the wooden roof truss members occasionally break, and the supports are misaligned	Partially collapsed	All collapsed
	Tile roof	No damage	A small amount of movement	Most appeared to move	A mass move to all tilt	—	—	—
	Steel reinforced concrete roof	No damage	No damage	No damage	Small cracks less than 1mm appear	There are small cracks with a width of 1-2mm, which can be used after repair	Cracks larger than 2mm appear	The load-bearing brick walls all collapsed, and the steel-reinforced concrete load-bearing columns were destroyed

Damage scale		DS1	DS2	DS3	DS4	DS5	DS6	DS7
		Almost no damage	Minor damage	Mild damage	Moderate damage	Secondary severe damage	Severe damage	Complete destruction
	Ceiling	No damage	A small amount of plaster falling	A large number of plaster falling	Wooden keel partially destroyed sagging seam	Collapse	—	—
	Inner wall	No damage	Plastering of slatted walls drops a little	Plastering of slatted walls fell heavily	Small cracks in the brick wall	Large cracks in the brick wall	Serious cracks in the internal brick wall to a partial collapse	Most of the brick wall collapsed
	Steel reinforced concrete column	No damage	No damage	No damage	No damage	No damage	Tilt	Large tilt

Table 3
K and ▯ values of different rock properties

Rock properties	K	▯
Hard rock	50-150	1.3-1.5
Medium hard rock	150-250	1.5-1.8
Soft rock	250-350	1.8-2.0

Table 4
Relationship between seismic intensity and physical quantities of vibration

Seismic intensity	Natural earthquake			Maximum vibration speed of blasting (cm/s)
	Acceleration (cm/s^2)	Speed (cm/s)	Displacement (mm)	
▯	50-100	4.1-8.0	21.-4.0	6.0-12.0
▯	100-200	8.1-16.0	4.1-8.0	12.0-24.0
▯	200-400	16.1-32.0	8.1-16.0	24.0-48.0
▯	400-800	32.1-64.0	16.1-32.0	>48

Table 5
Damage to surrounding buildings caused by the explosion of the West fertilizer plant in the United States

Serial number	Building name	Distance to epicenter (m)	Damage to buildings	Damage scale
A1	2-story wood light-frame apartment complex	166	Roofs complete blow out. East wall surface: collapsed completely; west wall surface: collapsed partially (the second story collapsed); north and south surfaces: façade collapsed completely, wall panels severely damaged. Wood framing destructed completely.	DS7
A2	A regular-shaped single-story residential house	174	A large area of Collapse. East surface destructed completely; a large area of façade collapse and wall panel destruction (south surface). East surface wall framing destroyed; large amount of roof truss failure.	DS7
A3	A single-family residential house	256	Very large deflections; several big holes. A large area of façade collapses (south surface). Failure of several roof trusses.	DS6
A4	A residential house	442	Shattering of all window glass on the east surface. Destruction of the garage door; several small-sized roof shingle torn offs.	DS4
A5	A residential house	526	All window glass is broken or Shattered. Destruction of garage door; small area of brick facade collapse (north surface).	DS4
A6	A school	827	There are small areas where the brick façade wall collapsed, corrugated wall panels and the garage door slightly buckled, and a few window glasses were broken. For the interior of the building, a lot of ceiling materials, e.g., boards, grids, and insulation materials, collapsed.	DS3

Table 6
Damage to surrounding buildings caused by an explosion in Tianjin Port, China

Serial number	Building name	Distance to Epicenter (m)	Damage to buildings	Damage scale
B1	Tianjin Port Public Security Bureau	400	There are only frames left in the 5-story office building	DS6
B2	Harbour City Community	800	The glass was shattered instantly, and the door frame and anti-theft door were damaged	DS3
B3	Tianbin Apartment	1000	The glass windows were all shattered, and the ceiling outer layer fell off	DS3
B4	TEDA Football Stadium	2000	Damaged external steel structure, glass, doors and windows	DS2
B5	China Automobile Research Institute Tianjin Branch	4000	The house was slightly damaged	DS2
B6	Jinmo Technology Company	5000	Office area was slightly damaged	DS1

Table 7
Damage to surrounding buildings caused by an explosion in Beirut Port, Lebanon

Serial number	**Building name**	**Distance to epicenter (m)**	**Damage to buildings**	**Damage scale**
C1	Marfa Modern Art Gallery	600	Almost completely destroyed	DS6
C2	Hotel Le Gray	1500	The huge force generated by the explosion blew through the walls of the hotel, the hotel furniture was also filled with shards of glass, and the carpet was scattered with glass slag.	DS4
C3	Lebanese Prime Minister's Office	1600	All doors and windows fell to the ground by the explosion	DS3
C4	Four Seasons Hotel Beirut	1850	The hall is full of dumped furniture and construction materials	DS3
C5	"Little China" Chinese Restaurant	3000	Damaged store	DS2
C6	Embassy of South Korea	7300	Two broken windows	DS2

Figures

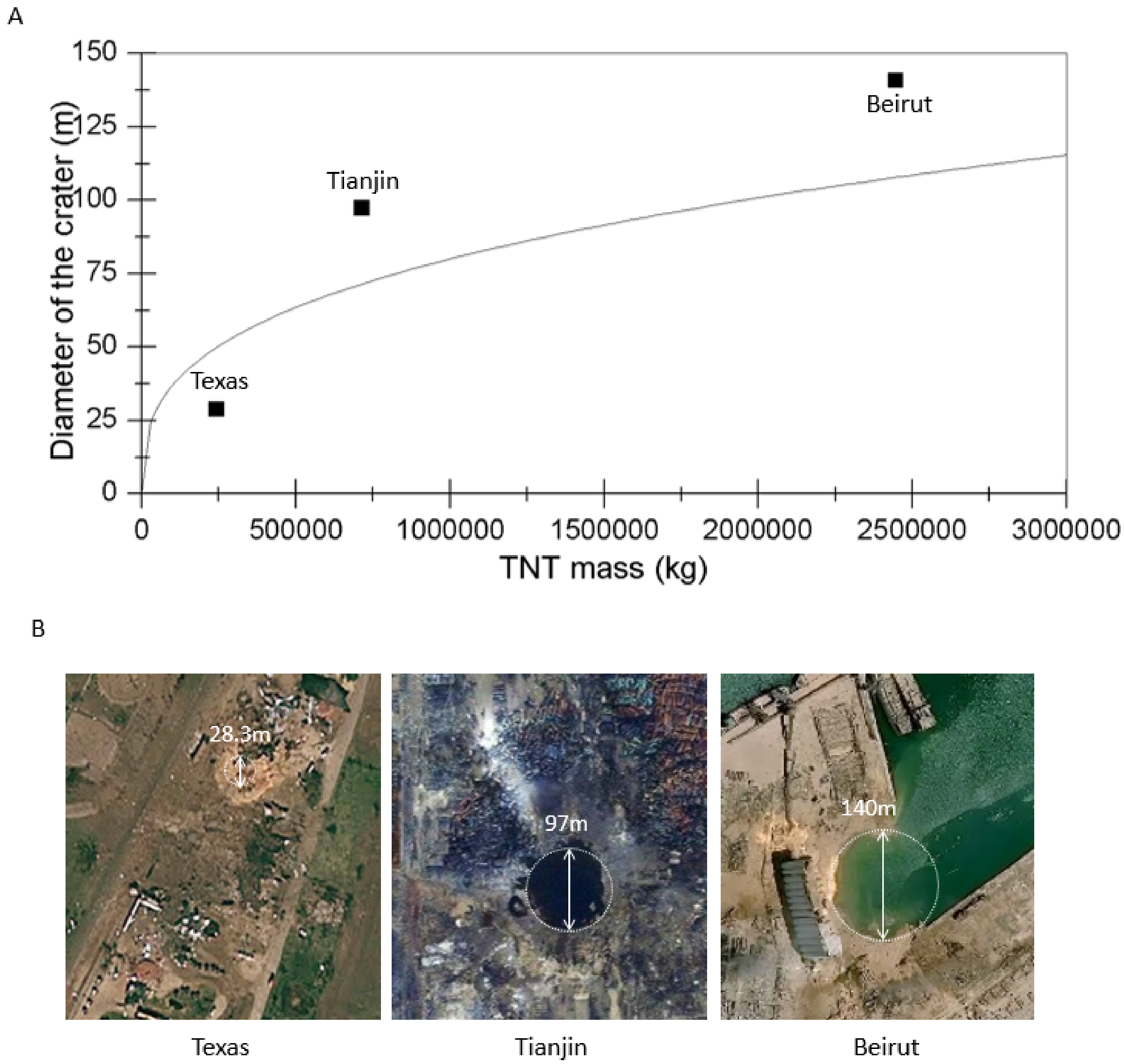


Figure 1

Comparison between the predicted and actual value of crater diameter in three explosion accidents. (A) Prediction curve and actual value of crater diameter. The Black Square represents the actual crater value. **(B)** A map of the crater size of the actual explosion. The double-arrowhead line represented the crater diameter.

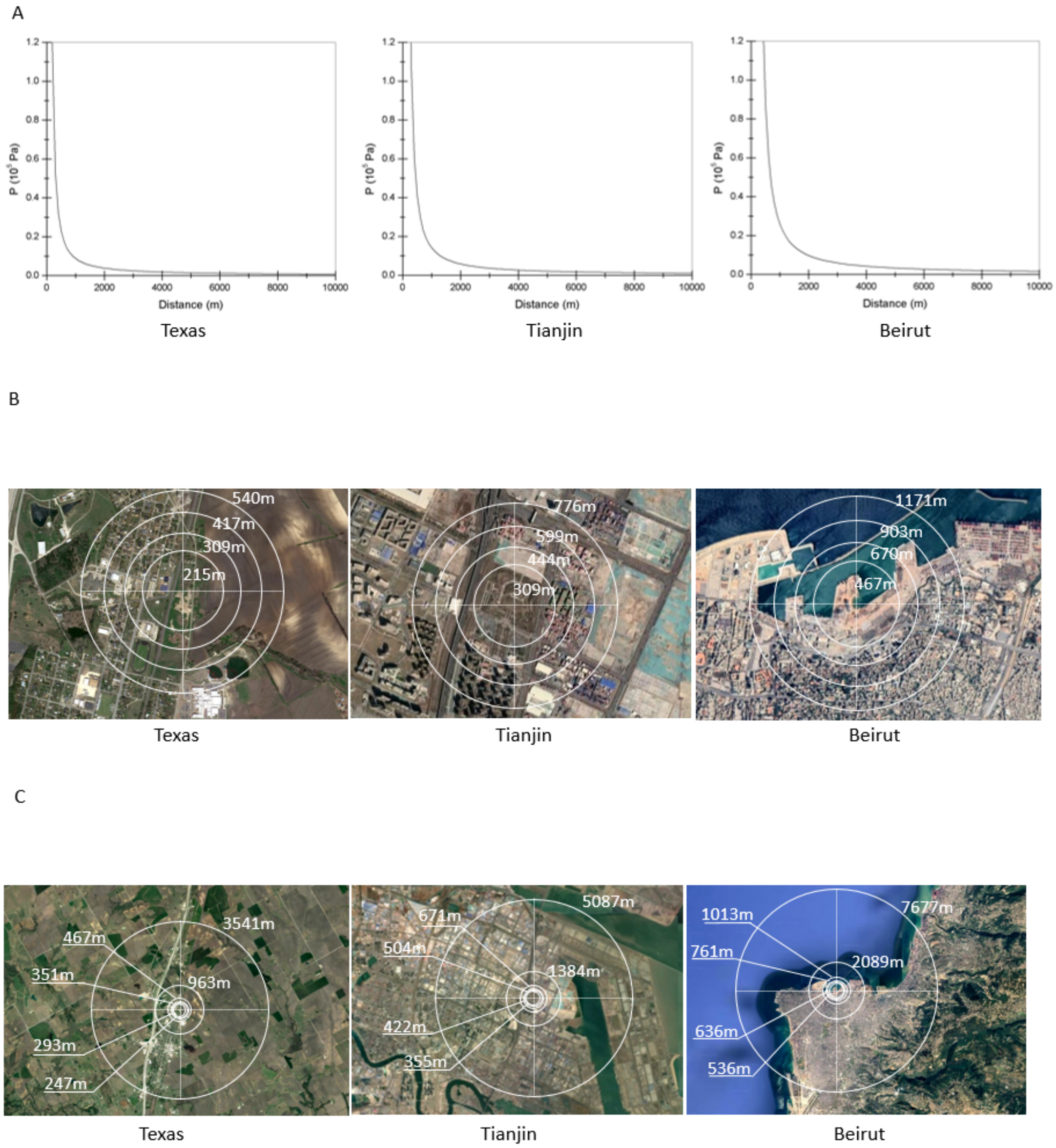
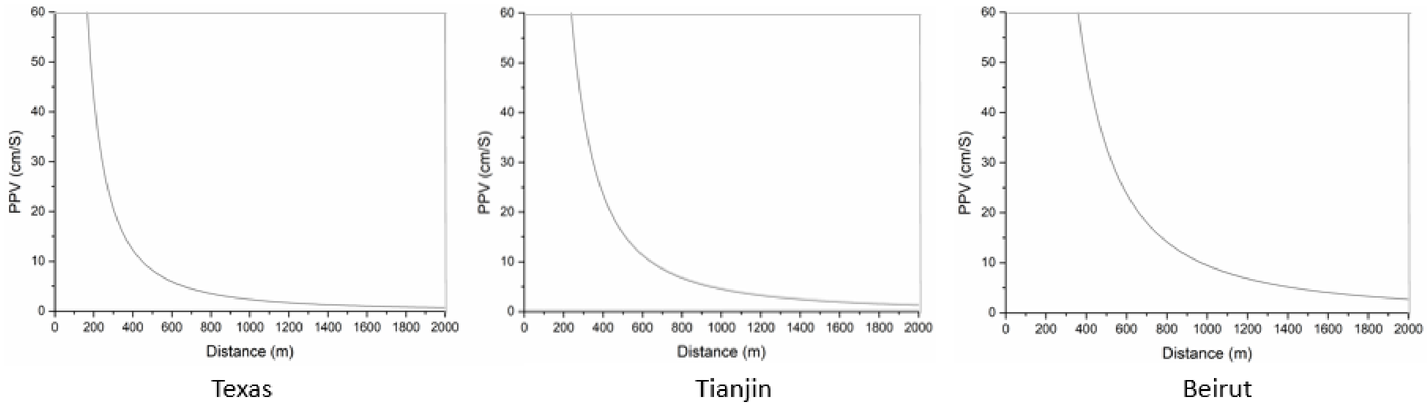


Figure 2

The influence of different distances on the change of air-blast overpressure and the predicted damage scale zones of casualty and building damage induced by air-blast overpressure. (A) The curve of air-blast overpressure varying with the distance from the epicenter of the explosion. **(B)** The predicted damage scale zones of casualties caused by air-blast overpressure**. (C)** The predicted damage scale zones of buildings caused by air-blast overpressure. (map data © 2013 Google)

A



B

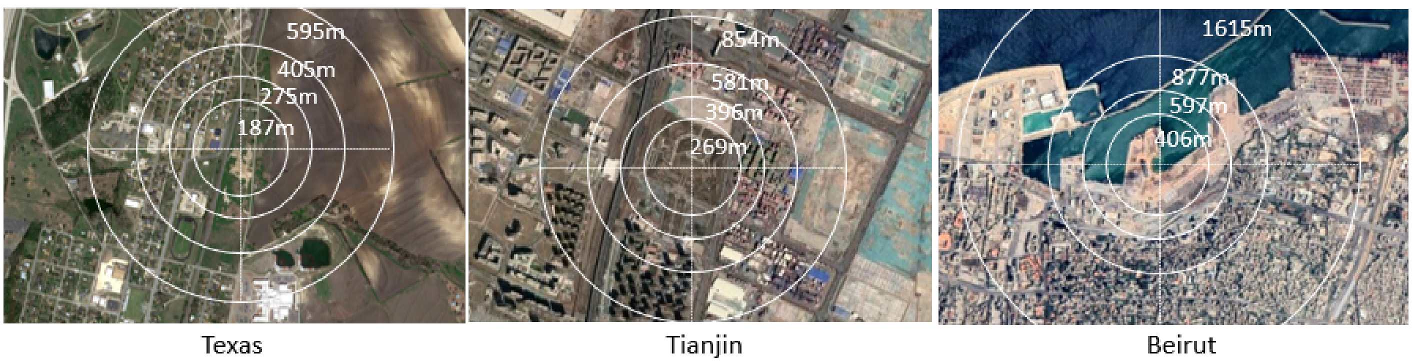


Figure 3

The influence of different distances on the change of ground shock and the predicted damage scale zones of casualty and building damage induced by ground shock. (A) The curve of ground shock varying with the distance from the epicenter of the explosion. **(B)** The predicted damage scale zones of casualties caused by ground shock. **(C)** The predicted damage scale zones of buildings caused by ground shock. (map data © 2013 Google)