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Finite Element Analysis Of a Real Man-made Disaster

Gerçek Bir İnsan Kaynaklı Felaketin Sonlu Elemanlar Analizi

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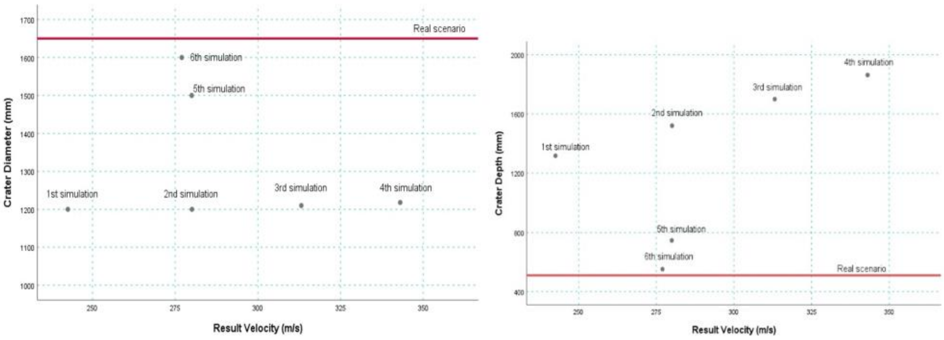
Highlight

This study examines a real chemical weapons attack that occurred on April 7, 2017 in the Han Sheikhun. The most remarkable result of the study is that the evaluation of ammunition and height, which is mentioned in official sources is consistent with the simulation results in our study

Bu çalışma, 7 Nisan 2017 tarihinde Han Şeyhun'da meydana gelen gerçek bir kimyasal silah saldırısını incelemektedir. Çalışmanın en dikkat çekici sonucu, resmi kaynaklarda belirtilen mühimmat ve yükseklik değerlendirmesinin çalışmamızdaki simülasyon sonuçları ile uyumlu olmasıdır.

Graphical Abstract



Abstract

Many software is used to analyse the effects of an explosion and its impact on other objects. ANSYS Autodyn is one such software. In this study, a real chemical weapons attack event that took place in Khan Sheikhoun, Syria on 4 April 2017 was simulated using ANSYS Autodyn software using the finite element method. The software was used to analyse whether the crater formed after the bombing event, whose boundary conditions (type and properties of the munition, properties of the ground, velocity of the munition and height of fall) and data are known, will be formed as a result of this collision and explosion. Looking at the results of the study, it can be seen that at the end of 6 different simulations, and especially as a result of the sixth simulation, the crater diameter converged to the real values by 97% and the crater depth by 92.4%. This strengthens the assumption that the ammunition in question was used in this incident.

Özet

Patlama ve patlamanın diğer cisimler üzerinde oluşturduğu etkilerin analiz edilebilmesi amacıyla birçok yazılım kullanılmaktadır. Bu yazılımların başında da ANSYS Autodyn yazılımı gelmektedir. Bu çalışmada, Suriye'nin Han Şeyhun şehrinde 4 Nisan 2017 tarihinde gerçekleşen gerçek bir kimyasal silah saldırı olayı, Sonlu elemanlar yöntemi kullanılarak ANSYS Autodyn yazılımı ile simüle edilmiştir. Yazılım, bombalama olayından sonra oluşan, sınır koşulları (mühimmatın türü ve özellikleri, zeminin özellikleri, mühimmatın hızı ve düşme yüksekliği) ve verileri bilinen kraterin, bu çarpışma ve patlama sonucunda oluşup oluşmayacağını analiz edebilmek için kullanılmıştır. Çalışmanın bulgularına baktığımızda, yapılan 6 farklı simülasyonun sonunda, özellikle de altıncı simülasyon sonucunda krater çapının %97 oranında krater derinliğinin ise %92,4 oranında gerçek değerlere yakınsadığı görülmektedir. Bu da söz konusu mühimmatın bu olayda kullanıldığı varsayımını güçlendirmektedir.

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1. INTRODUCTION

Chemical, biological, radiological, and nuclear (CBRN) incidents are man-made disasters that can be large or small scale. These include chemical, biological, radiological, and nuclear weapons [1]. CBRN events are low-frequency disasters that affect a large number of people and cause fear and panic in society when they occur [2]. For effective CBRN-based disaster event management, which includes planning, preparation, response, and recovery phases, various simulation programs are used [3]. A chemical weapon is “any chemical which, through its chemical effect on living processes, may cause death, temporary loss of performance, or permanent injury to people and animals” [4]. Chemical weapons have been around for centuries and have been employed extensively throughout history, much like explosives. Evidence of a Persian army assault on Roman forces in AD 256, which resulted in the deaths of at least 20 soldiers by burning sulfur and bitumen, which produces a toxic haze, has been discovered in what is now Syria [5]. Explosives are solid or liquid chemical compounds or mixes that may conduct a fast chemical reaction without the requirement for an additional external reactant, such as oxygen from the atmosphere. They are typically meta-stable. A chemical compound, like nitroglycerin (NG), is a pure substance created when two or more elements combine to form a new material that loses its properties due to the formation of a bond. This reaction is an exothermic one that happens quickly and produces a lot of heat, light, gas, sound, and pressure when it is triggered by collision, friction, heat, spark, flame, or shock [6]. ANSYS Autodyn is a powerful and useful finite element analysis program that can perform explicit analysis and allows many simulations, including explosions and high-speed collisions. It is primarily used in the defense industry [7]. The Ansys Autodyn program is useful software that uses the finite element analysis method to simulate the effects of an explosion [8].

Germany was the pioneer in modern warfare when it came to the use of chemical weapons and the introduction or creation of new chemical agents in response to advancements in protective gear. Many of Germany's chemical weapons were designed by Fritz Haber [9]. On October 27, 1914, Germany launched tear gas-filled shells at the British near Neuve Chapelle, marking the start of their employment of chemical weapons in war [10]. The August 2013 chemical weapons strikes in Ghouta, Syria, claimed the lives of around 1400 people [11, 12]. With the ongoing domestic unrest in Syria and the increased activities of terrorist groups such as ISIS, there have been multiple chemical weapons attacks in the country [13]. The most notable of these strikes were those on Kharbit Masasnah, Yarmouk, Al Balil in 2017 and Khan Sheikhun, Qalib Al-Thawr and Al Salamiyah and Souran Aleppo in 2018. The Salisbury and Amesbury occurrences in England and the incident in Malaysia are the most significant events in our recent history, excluding these attacks [14].

In this study, the impact of the M4000 chemical bomb allegedly used in the city of Han Sheikhun in Syria, which is one of the above-mentioned incidents of chemical weapons use, and the effects of this explosion were modeled with Ansys Authodyn Finite Element Analysis software. The main purpose here is to both re-simulate a real-world event and compare the crater diameter and depth that are formed when the M4000 air-dropped bomb hits the ground under certain boundary conditions with the simulation data.

2. A REAL MAN-MADE DISASTER (EXPERIMENTAL STUDIES)

2.1. What happened in Khan Skeykhun?

In Syria, the government and opposition forces have fought bloody battles to keep the city of Khan Sheikhun, which is also the subject of this study and is in a critical geopolitical position [15]. On the morning of April 4, 2017, with a sunny, windless and clear sky, as the city dwellers began a new day, the sound of a jet plane [16]. In the early morning of 4 April, public reports emerged that air strikes had released sarin in the town. The UN COI reported that "photographs of weapon fragments depict a chemical aerial bomb of a type developed in the former Soviet Union." The UN COI also stated that "the chemical bomb killed more than 80 people and injured approximately 300 people" [15]. In the judicial investigations carried out by the United Nations and the Organization for the Prohibition of Chemical Weapons, it is stated that the Russian-made M4000 airdropped bomb containing a chemical warfare agent (Sarin gas) was used in this incident [17]. On the morning of April 4, 2017 an incident involving sarin killed approximately 100 people in Khan Shaykhun and affected another 200 people who survived acute exposure [18]. On the basis of samples obtained during autopsies and from individuals undergoing treatment in a neighboring country, those who undertook the fact-finding mission of the Organization for the Prohibition of Chemical Weapons concluded that the victims had been exposed to sarin or a sarin-like substance. The extensive information independently collected by the Commission on symptoms suffered by victims is consistent with sarin exposure [15].

2.2. Analysis On Explosion Crater

The type of ammunition, its properties, and its explosive content were all reported in the official UN reports following the conclusion of the legal investigation, along with the diameter and depth of the crater left by the explosion. However, assumptions are made regarding the height at which the ammo falls, the angle at which it hits the ground, and the properties of the asphalt and soil it hits. Forensic investigations were conducted into the incident, and scientific data was explained. The purpose of this article is not to accuse or exonerate any country. The aim of the article is to investigate whether the diameter and depth of the crater formed as a result of the explosion are compatible with the values calculated by the finite element method.

The crater opened by the explosion was examined before the ammunition containing the chemical agent was modeled with the Ansys Workbench. Photographs of the crater are provided in Figures 1 and 2.

Figure 1: Post-Explosion Crater Photo [19].

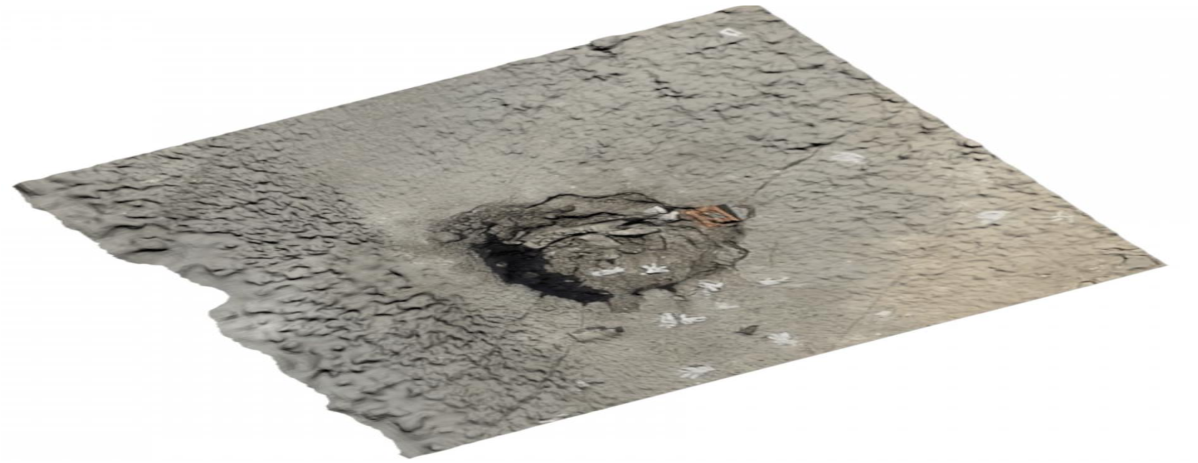

Figure 2: Post-Explosion Crater Photo [19].

When the OPCW's report [20] is examined, it is understood that the diameter of the crater varies between 1.5 m and 1.65 m, and the depth of the crater varies between 42 cm and 51 cm.

When Figure 2 is examined, it is seen that the asphalt thickness is about 15 cm. The part where the asphalt is located is taken as 0.15m x 6m x 6m and the soil part under the asphalt is taken as 2.5m x 6m x 6m.

3. MATERIAL AND METHOD

The simulation studies were carried out with the Ansys Workbench package program on a computer with Windows 10, 64 Bit Operating System, 16 GB of Ram, and an Intel Core i7 7700 k CPU 4.2 GHz processor. With simulation studies, error messages were received many times until realistic results were obtained, and it took days to debug these errors. The most common error is the time step being too small. Because the mesh elements of the ammunition contain very small elements, the duration of analysis is approximately 150 hours.

In addition, the modeling was done with the explicit analysis method, and the results were studied in very small time intervals (on the order of milliseconds). The end time was taken as 0.005 seconds, and the analysis of this time interval took approximately 150 hours. The literature was reviewed to decide on the optimum ending time. The collision of the Scud Missile with a weight of 227 kg and a speed of 250 m/s at an angle of 15 degrees to the stone and soil ground was modeled using the Finite Element Analysis method in a study conducted at the Lawrence Radiation Laboratory in Livermore, California [21]. Figure 3 shows that more than 95 percent of the ground penetration is completed in 0.005 seconds. In addition, in another study conducted at Lawrence Radiation Laboratory in Livermore, California, 90% of the TNT explosion reaction was completed in 80 nanoseconds (8x10-8 seconds), while the remaining 10% was completed in 200 nanoseconds [22]. At the same time, if the end time is 0.01 seconds or longer, the analysis time will increase to 300 hours or more.

Additionally, the end time has been set as 0.005 seconds since it is aimed to use the resources effectively.

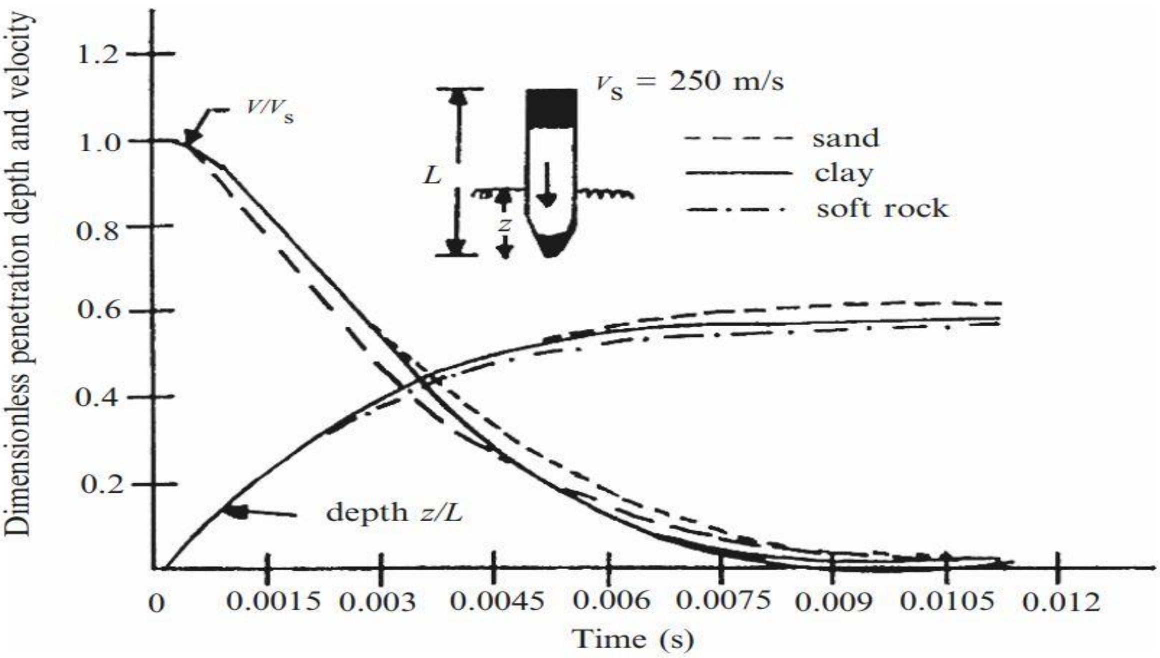

Figure 3: Penetration Depth, Time And Velocity Relationship In Sand, Clay And Rock Soil [22].

In the study, the possibility of the ammunition containing the chemical agent (sarin gas) was considered for the Russian-made M4000, an airdropped bomb. The features of the Official Report and the M4000 Bomb have been compared, and it is understood that the disapproval is compatible. The data on ammunition in UN Report S/2017/904 [17] is presented in tabular form in Table 1.

Table 1: Brief Information On Ammunition And Official Documents Passing This Information.

	Type of Ammunition	**Weight of Ammunition**	**Diameter of Ammunition**	**Amount of TNT Contained**
Related Page of the Report	Page 28	Page 28	Page 28	Page 26
Paragraph Number in the report	56	53	57	47
Statement in the Report	Compatible with the structure of air-dropped chemical Bombs used in Syria	Between 300-500 kg	300-500 mm	than 10 kg TNT
Feature of the M4000 Air-Drop Bomb used in our calculations	Chemical Weapons used in Syria are of Russian origin, as in the M4000, and are of the type of air-dropped bombs in the M4000.	350 kg	460 mm	3.6 kg of TNT

The information that two types of chemical weapons, M4000 and MYM6000, were used in Syria during the inspections carried out by the Organization for the Prohibition of Chemical Weapons and the United Nations Auditors was published in the relevant report [20].

In the CAD model uploaded to the ANSYS Workbench, all materials related to ammunition are introduced to the system with the "Material Assignment" process. Soil and asphalt data for the road where the bomb fell were entered into the system. Data on the deformation of the structural steel was entered into the system using the Johnson-Cook Material and Deformation Model. Data on ammunition are given in Table 2.

Table 2: Data About Ammunition.

Outer material of ammunition	**Structural Steel**
The outer thickness of the bomb	4mm
Weight of the bomb	350 kg
The chemical agent and its amount	Sarin , 250 kg
Diameter of the bomb	460 mm
length of the bomb	1570 mm
Explosive and quantity found in the bomb	TNT, 3.6 kg

In the first model, it was assumed that the ammunition hit the ground at a 90-degree angle for ease of solution. In light of the data in the United Nations Security Council's report numbered S/2017/904, it is known that the ammunition was dropped from a height of 4000–10,000 meters [17]. The velocity of the ammunition when it hits the ground when its initial velocity Vx and Vy is 0 and it is released in free fall from a height of 4000 meters;

$V2= 2hg$ ($g= 9.8$ m/s^2) (3.1)

$V2= 2 \times 4000$m $\times 9.8$ m/s^2

V= 280 m/s

As shown in Figure 4, the research conducted in light of these data revealed that the crater's diameter was 1200 mm and its depth was 1520.8 mm.

While the crater diameter was 27% less than the real value, the crater depth calculated by computer analysis was 198% higher than the real value.

As can be seen, when the bomb hits the ground at a speed of 280 m/s from a height of 4000 meters, it penetrates deeper than expected and creates a smaller crater diameter than expected.

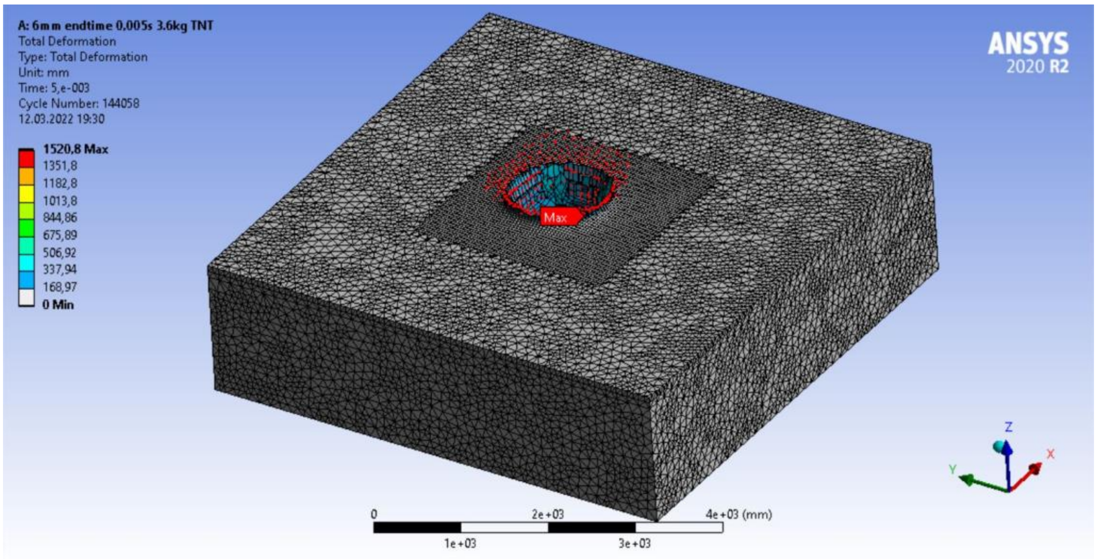

Figure 4: Crater Depth Of The Bomb Hitting The Ground At 280 m/s.

For the bomb dropping from 3000, 5000, and 6000 meters, all the operations for the fall from 4000 meters were repeated, and the summary information of the results obtained is presented in Figures 5, 6, and 7. These steps were not repeated between 6000 and 10,000 meters in order to use the time efficiently because the crater depth is much greater than it should be.

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According to the analysis's findings, a bomb dropping from a greater height accelerates more quickly and creates a larger crater. Figure 5 depicts how altitude affects velocity, whereas Figure 6 depicts how height affects crater depth. The rise in the altitude-velocity graph and the altitude-crater depth graph is also nonlinear.

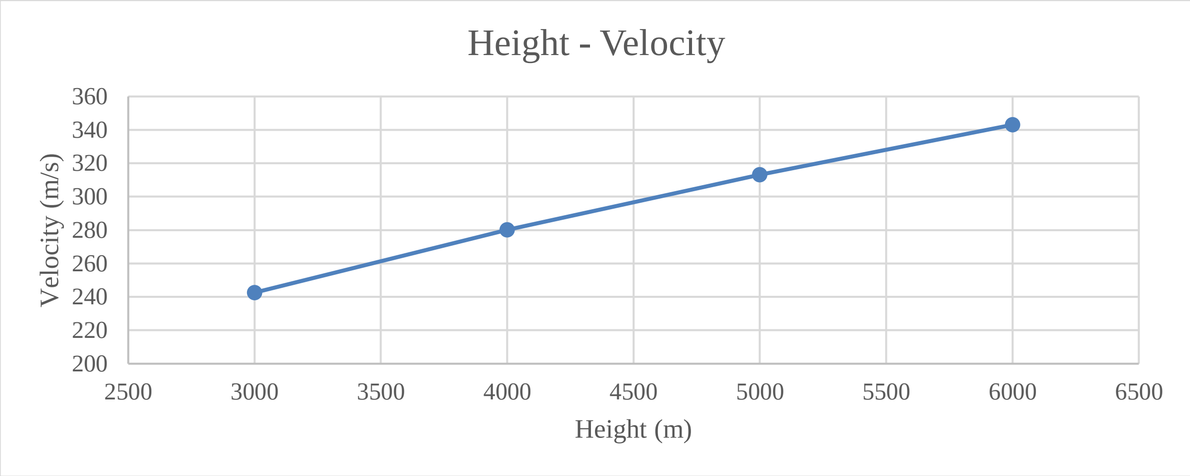

Figure 5: Height vs Velocity Graph.

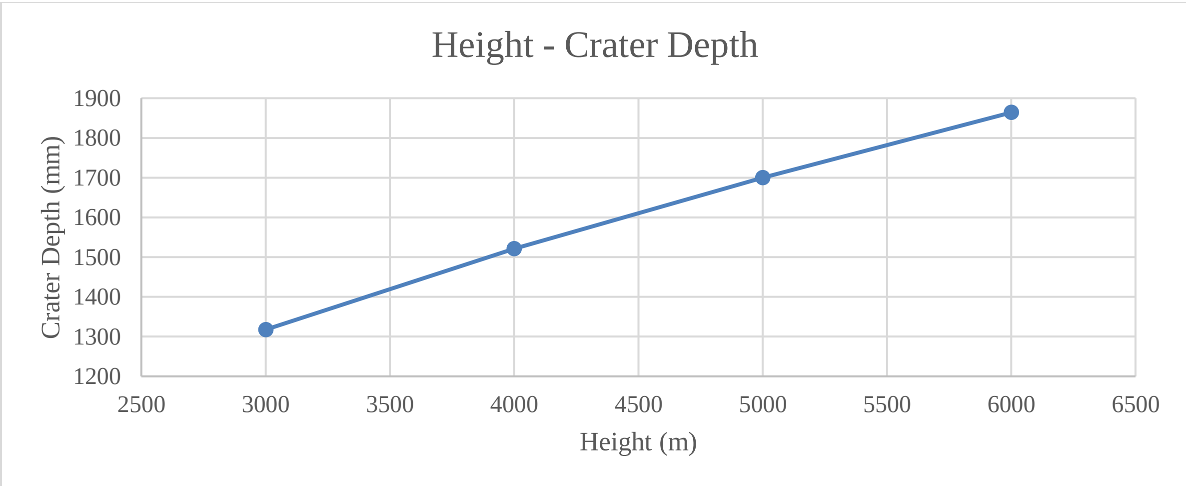

Figure 6: Effect Of Height On Crater Depth.

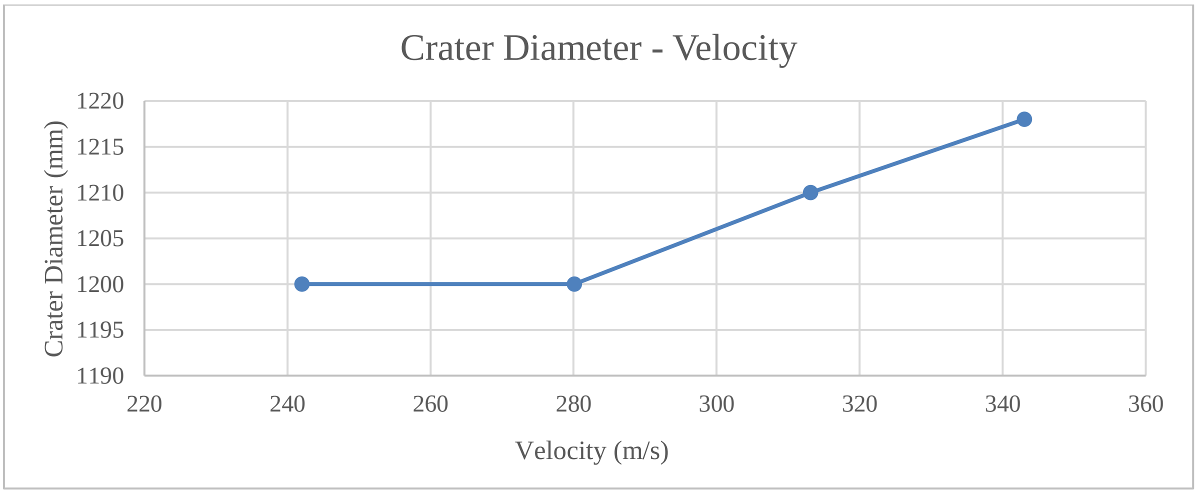

Figure 7: Effect Of Impact Velocity On Crater Diameter.

The bomb dropped from above strikes the ground at a 90-degree angle, and the calculations up to this point have been based on the assumption that the bomb's initial horizontal velocity is zero. The crater diameter is not significantly affected by the horizontal velocity of the bomb; hence, it is inferred that the bomb must also have a horizontal velocity. Although it was assumed that the initial velocity of the bomb horizontally was zero in the previous analyses, the speed of the aircraft was also taken into account in the analyses to be made after that, and the horizontal velocity of the aircraft was included in the calculations as the horizontal velocity of the bomb.

The report with the reference number A/72/615-S/2017/938 [23] claimed that the bomb impacted the ground at a -55.6 degree angle and that the aircraft's horizontal speed was 800 km/h (225.1 m/s). The package program made use of this data, and the outcomes were evaluated.

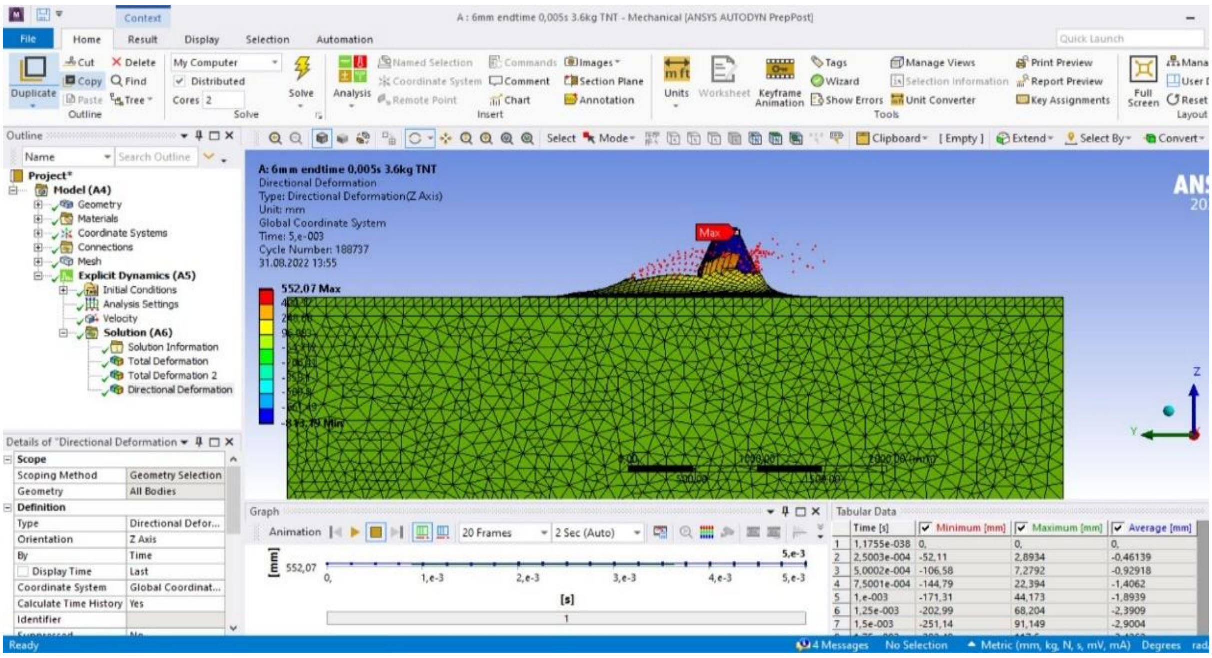

Figure 8: Crater Depth Of The Bomb Hitting The Ground At Vx=225.1 m/s, Vy=161.42 m/s.

In the final simulation, the crater depth calculated in the analysis is 7.6% greater than the real depth. The calculated crater diameter is 3% smaller than the actual diameter. The results closest to the actual values were obtained in the sixth and final analysis.

When the work done thus far and the Figure 1 & 2 are examined, it is clear that the bomb remains in the crater are leaning against the crater wall. Although it is unknown how many degrees the bomb dropped from the aircraft when it hit the ground, it is assumed that it hit the ground at an angle due to the aircraft's speed. As can be seen in Figure 8, when the results of the studies with an aircraft speed of 800 km/h (225.1 m/s) are examined, it is seen that the crater diameter is compatible with the real values.

4. RESULTS

When Figures 9 and 10 are compared, it is clear that the 5th and 6th horizontal velocity simulations are very close to the real values.

Especially with the sixth simulation, the results were 97% close to the actual values, and when crater depth was taken into account, the results were 92.4% close to the actual values. Table 3 shows the horizontal, vertical, and resultant velocities for the six simulations.

Table 3: Data For Height, Horizontal Velocity, Vertical Velocity And Resultant Velocity.

Analysis No	Height (m)	Downtime (sec)	V_x Velocity (m/s)	V_y Velocity (m/s)	Result Velocity (m/s)
1	3000	24,73	0	242,57	242,57
2	4000	28,56	0	280,09	280,09
3	5000	31,93	0	313,15	313,15
4	6000	34,98	0	343,04	343,04
5	4000	24,73	225,1	161,42	277
6	4000	24,73	225,1	146	268,3

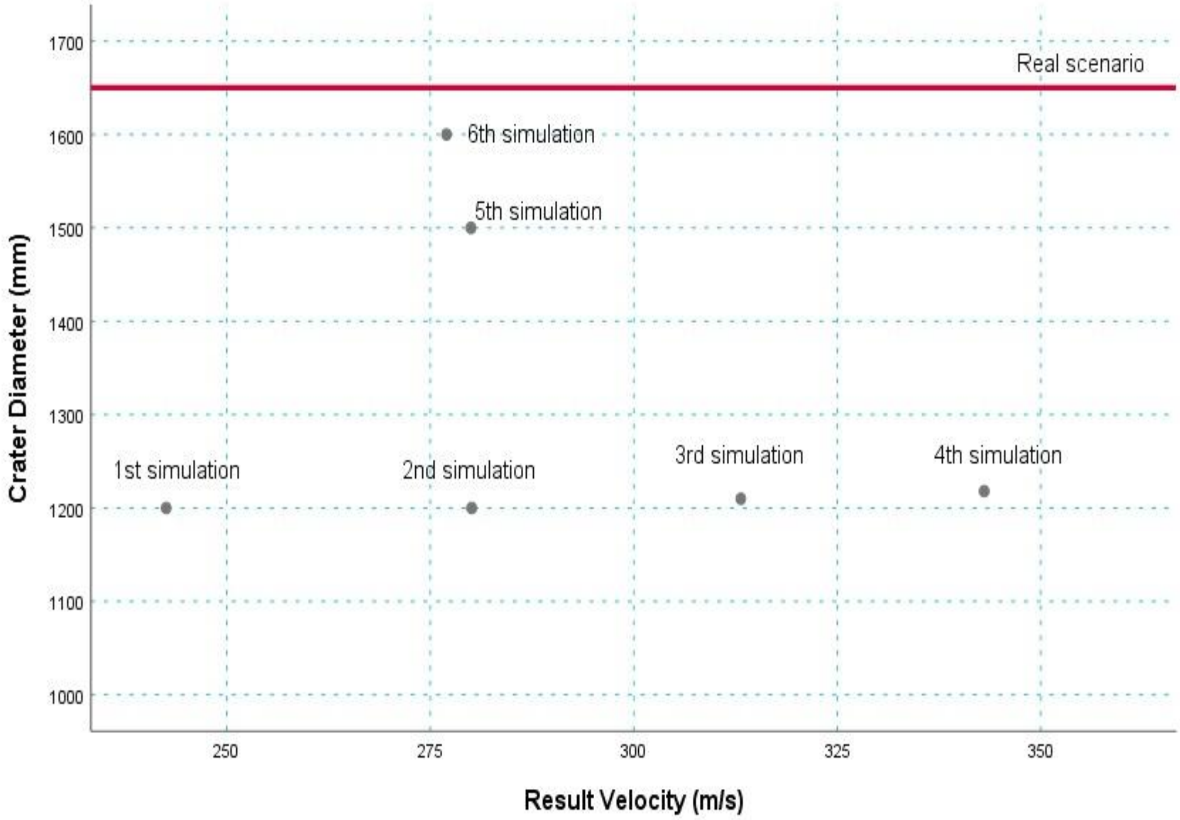

Figure 9: Data For Resultant Velocity – Crater Diameter For Six Simulations.

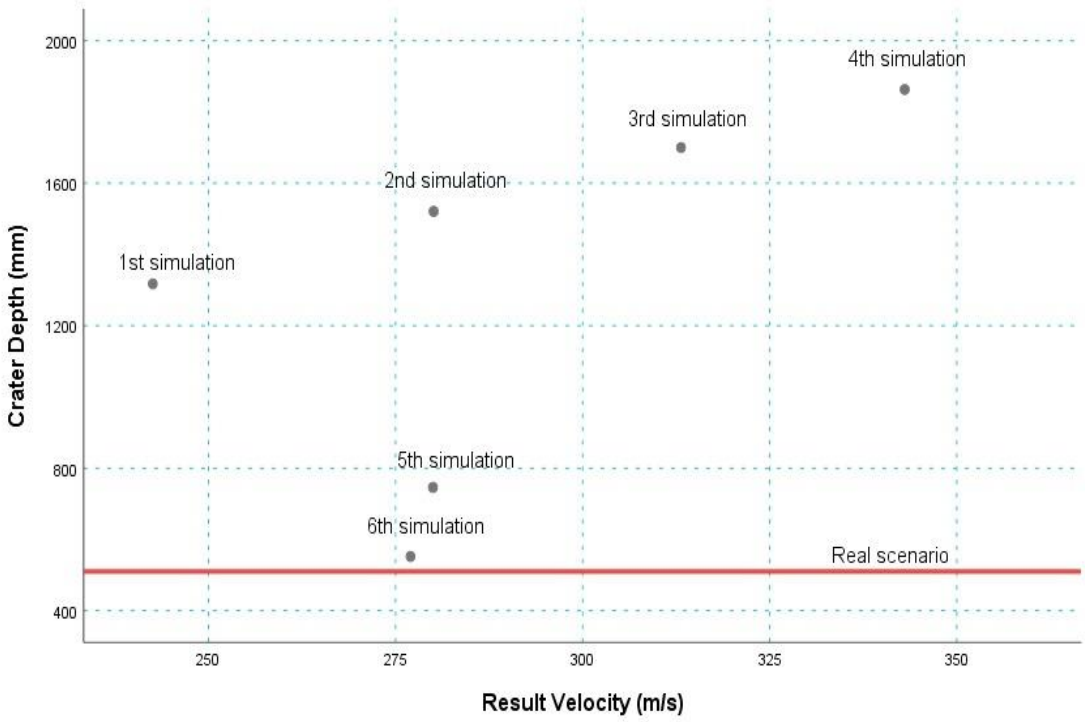

Figure 10: Data On Resultant Velocity – Crater Depth For Six Simulations.

5. DISCUSSION

Because working with explosives and examining the results of explosions is costly and subject to legal restrictions, many analyses in the defense industry are performed using software that employs other finite element analysis methods, particularly the ANSYS Workbench (Autodyn module). This study examines a real chemical weapons attack that occurred on April 7, 2017 in the Syrian city of Han Sheikhun. The ANSYS Workbench (Autodyn) program was used to analyze the attack's mathematical data. The most important result of the study is that the evaluation of ammunition and height, which is mentioned in official sources [20,23], is consistent with the simulation results in our study.

Following the collection of scientific data in the post-explosion crime scene investigation processes, various scenarios were studied using the inductive technique, and conclusions were drawn about the bomb's speed and the height at which it was dropped. Because the fuse part of the bomb is effectively impacted, the fuse must hit the ground for the bomb to explode. As a result, scenarios involving the horizontal impact of the bomb on the ground are excluded from this study. According to official reports [17, 23], the bomb could have been dropped from a height of 4000 to 10,000 meters. The M4000 ammunition was modeled from a height of 4000 meters, with an initial velocity of 0 both horizontally and vertically, and hitting the ground in free fall in the first analysis. The aircraft's speed was ignored in this case, and it was determined whether the diameter and depth of the crater that the bomb would open after detonation would be equal to the actual crater diameter and depth.

The bomb was dropped from 4000 meters with zero horizontal velocity in the first analysis, and it was observed that it reached a depth greater than the expected crater depth. The analysis for 4000 meters of altitude was repeated based on 3000, 5000, and 6000 meters of altitude to understand the effect of altitude and velocity on crater diameter and depth. The impact velocity increased nonlinearly as the height of the bomb dropped, and thus the crater diameter increased nonlinearly as well. Furthermore, the height and, as a result, the increase in velocity did not result in a significant increase in crater diameter.

Given that vertical velocity has little effect on crater diameter and the TNT load of the bomb is constant, it should be noted that the bomb must have both vertical and horizontal velocity (aircraft velocity). According to another UN report [23], the Su-22 aircraft that dropped the M4000 bomb reached a horizontal speed of 810 km/h (225.1 m/s), and the bomb hit the ground at an angle of 55.6°.The results of the analysis performed with these data were found to be very close to the actual values.

When the photographs (Figures 1 and 2) from the incident are examined, it is clear that the body parts of the ammunition are in the crater adjacent to the rim of the crater, just as they were in the previous ANSYS Workbench analysis. This lends support to the theory that the bomb has a horizontal velocity when released. Furthermore, the 3.5 kg TNT load used in the bomb is insufficient to completely shatter a 350 kg bomb. The explosive, which is about 1% of the total weight, only allows the sarin chemical agent to spread out of the bomb by tearing the bomb's body. In this respect, the size of the opened crater depends on the crash of a 350 kg object falling from a very high height rather than the effect of the explosion.

Due to the fact that the issue can be politically misleading and is a new topic, there is only one study on this issue in the literature. Goong C. et al. [24] examined the event in Han Sheikhun with another Finite Analysis Method software, LS Dyna, in their 2020 study. Goong et al. conducted this study under the assumption that the ammunition found around the crater could be a 122-mm rocket. In this regard, the type of ammunition, the angle of impact with the ground, the speed of the ammunition, and the software used differ from those used in our study. In our study, the United Nations inspection reports were examined, and the mathematical data was taken from official reports [20,23], not from the press or other parties that might be biased. In the study of Goong et al. [24], the diameter of the crater is around 1.2 m, while the depth of the crater is well over 2 meters. Considering the crater diameter and depth, our study is much closer to the actual values than Goong et al. The reason for this is that the ratio of the explosives in the ammunition thought to have been used in our study to the total weight of the ammunition is only 1 percent. In the ammunition in the study by Goong et al., this ratio was 23.5 percent. Therefore, the explosive in the munition analyzed in our study may have only torn the jacket of the munition and caused less damage to the ground. In Goong et al.'s study, on the other hand, since the amount of explosive was relatively higher, the crater depth may have been greater as a result of the explosion. The comparison of the data obtained from both studies is presented in Table 4.

Table 4: Literature Comparison.

Data	Dereli et al	Goong et al
Software	Ansys AUTODYN	LS DYNA
Munition Type	M4000 Aerial Bomb	122 Artillery Rocket
Explosive Payload	3,5 kg	6,35 kg
Total Mass of the Ammunition	350 kg	27 kg
Velocity of Munition	268,3 m/s	220 m/s
Impact Angle of the Munition	55,6	65
Calculated Crater Diameter	1600 mm	1200
Actual Crater Diameter	1650 mm	
Percentage Difference Between Actual Value of Diameter	3 %	25 %
Actual Crater Depth	510 mm	
Calculated Crater Depth	552,07 mm	2000
Percentage Difference Between Actual Value of Depth	7, 6 %	362,2 %

6. CONCLUSION

In this study, simulations of the crater formed as a result of the chemical weapons attack were created using scientific data from the forensic investigation that was carried out and completed, avoiding political discussions about which country did what and why. The Ansys Autodyn program and the Finite Element Analysis Method were used to analyze the crater diameter and depth of the explosion in Han Sheikhun. When the data obtained from official reports regarding the height and angle of impact of the munition were used and the simulation created with the help of a computer program was compared with the actual values, it was found that 97 percent of the crater diameter and 92.4 percent of the crater depth coincided with the actual values. In this case, it can be said that the last simulation of the crater formed as a result of the impact of the bomb dropped by an aircraft with a horizontal speed of 810 m/s from a height of 4000 meters with an angle of 55.6 degrees has the closest results to the real values. This result strengthens the possibility that M4000 ammunition was used in this incident

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AUTHOR CONTRIBUTIONS

Caner DERELİ: Conceptual design, Data curation, Analysis, Funding acquisition, Research, Methodology, Project management, Resources, Software, Audit, Approval, Visualization, Writing-Draft, Writing Reviewing, Editing, and Experimental studies.

Murat ŞAHİN: Conceptual design, Data curation, Research, Methodology, Project management, Resources, Software, Approval, Writing-Draft, Writing Reviewing, and Editing

CONFLICTS OF INTEREST

Yazarlar, herhangi bir çıkar çatışması olmadığını beyan eder.

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