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Protection Capability of Different Types of Barricades Against Blast Pressure

Farklı Barikat Tiplerinin Patlama Basıncına Karşı Koruma Kapasitesi

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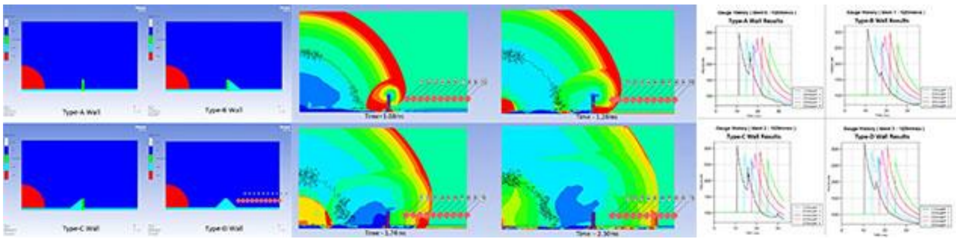
Highlights

Barricades are among the primary measures that can be taken against the destructive effects of explosions. The protective capacity of different barricade types is crucial for proper design. The purpose of this validated numerical analysis is to examine the interaction between the pressure from the explosion and the geometric structure of the barricades.

Graphical Abstract



Abstract

Pressure waves created by explosions caused by various reasons such as industrial accidents or terrorist attacks interact with the barricades used for protective purposes and can lead to complex pressure distributions and regional load increases. This situation can cause the barricades not to fully fulfill their expected protective role and increase risks in certain regions. To address this critical issue, the present study conducted a detailed investigation of the performance of common barricade types with various geometric designs against blast pressure. This investigation employed a numerical analysis method using AUTODYN software, corroborated by experimental verification. The analyses performed clearly revealed that the geometric form of the barricade plays a critical role in determining the reflection, damping and transmission characteristics of the pressure waves and thus directly affects the level of protection. The obtained data provide a concrete basis for the development of more effective and optimized barricade designs that will increase the safety of life and property in areas that may be exposed to explosion loads.

Özet

Endüstriyel kazalar veya terör saldırıları gibi çeşitli nedenlerle meydana gelen patlamaların oluşturduğu basınç dalgaları, koruma amaçlı kullanılan barikatlarla etkileşime girerek karmaşık basınç dağılımlarına ve bölgesel yük artışlarına yol açabilir. Bu durum, barikatların beklenen koruma rolünü tam olarak yerine getirememesine ve belirli bölgelerde risklerin artmasına neden olabilir. Bu kritik sorunu ele almak için, mevcut çalışmada çeşitli geometrik tasarımlara sahip yaygın barikat tiplerinin patlama basıncına karşı performansı ayrıntılı bir şekilde incelenmiştir. Bu araştırmada, deneysel doğrulama ile de desteklenen AUTODYN yazılımı kullanılarak sayısal bir analiz yöntemi kullanılmıştır. Yapılan analizler, barikatın geometrik formunun basınç dalgalarının yansıma, sönümleme ve iletim özelliklerini belirlemede kritik bir rol oynadığını ve dolayısıyla koruma seviyesini doğrudan etkilediğini açıkça ortaya koymuştur. Elde edilen veriler, patlama yüklerine maruz kalabilecek alanlarda can ve mal güvenliğini artıracak daha etkili ve optimize edilmiş barikat tasarımlarının geliştirilmesi için somut bir temel oluşturmaktadır.

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1. INTRODUCTION

An explosion can occur suddenly and uncontrollably. Because the resulting effects of an explosion are so dangerous, special precautions must be developed. Barricades are actively used to reduce the spread of bursts and pressure effects. While the position and design of barricades are decisive factors in their performance, their relationship with pressure is the primary focus of this research.

Determining the behavior of the blast wave pressure generated by the explosion is important in order to take the right precautions against it. Blast propagates as a mechanical wave. The behavior of that wave during its propagation changes according to the environment or objects it interacts with. The situations such as the direction, reflection or accumulation of the blast wave pressure caused by the interaction with the environment are possible situations for the blast wave as in all other mechanical waves. Such behaviors can be a determining factor for the effects of the blast wave on the environment. Although there has been a great deal of work done on open-air free explosions, studies on areas where blast waves are likely to interact have been more limited. The reason for the limited number of these studies is that they include very different scenarios. Understanding the general principles and studies on the interaction behavior of blast waves with the environment are very important for the creation of safe environments [1,2].

Experimental studies have been carried out for many years to reveal the effects of explosions. As a result of these studies, empirical and semi-empirical methods have been developed. These methods are actively used in many areas. Empirical and semi-empirical methods generally cover simple environments and assumptions, but these methods are not sufficient for special cases. Numerical analyses come to the fore in determining special cases. There are many applications that perform such studies. All of these applications are created on the same methods. AUTODYN, LS-DYNA, Air3D, ABAQUS are well-known programs and are based on similar hydro codes and EOS [3-5].

The verification of numerical analyses can be done with experimental methods or reliable empirical methods. Studies can be diversified from the basic model on which verification is made. Numerical studies are expected to have a certain orientation and are desired to approach the final information. This approach is aimed to form the logical basis of the studies.

Chapman et al. [6] present a parametric approach to the use of the AUTODYN2D hydrocode to simulate the interaction of blast waves with structures. The main objective of the study was to determine the effect of input parameters, particularly grid size and synthetic viscosity values, on the accuracy of the simulation results. The outputs of the numerical model were validated against established experimental data for simple geometries and a complex geometry experiment. The findings show that AUTODYN2D can model blast wave propagation and structural loading with high accuracy, provided that the parameters are carefully selected. The study highlights that such numerical tools represent an effective alternative to costly physical experiments.

Shin et al. [7] numerically model the effects of near-field detonation of high explosives using the

AUTODYN CFD (Computational Fluid Dynamics) code. The study aims to characterize the incident and reflected overpressure and impulse values near the explosion center, where standard empirical methods are inadequate. The paper investigates the effects of cell size, afterburning phenomenon and boundary conditions on the results through 1D, 2D and 3D simulations. The main findings show that the Friedlander waveform cannot represent the near-field pressure history due to complex interactions such as expansion of the explosion products and Mach body formation.

Rose and Smith [8] study the effects of geometric parameters (street width and building height) on positive and negative phase blast impulses in urban explosions. A parametric methodology including numerical simulations validated with small-scale experiments is used. The findings show that confinement by buildings significantly increases positive impulse. Negative impulse is found to exhibit a more complex behavior, increasing with building height and decreasing after a certain height. The study emphasizes that negative phase impulse can exceed positive phase after a certain distance and this situation should not be ignored in structural damage analyses.

Fan et al. [9] study model the near-field blast loads caused by cylindrical explosives by considering the explosive geometry and detonation configuration. The research combines field experiments and systematic numerical analysis; a high-precision finite element model based on AUTODYN is validated with experimental data. The study quantitatively analyzes the effects of explosive shape, length-to-diameter (L/D) ratio, orientation, and detonation point on the incident peak pressure and impulse. The findings show that the secondary peak overpressure caused by cylindrical explosives is particularly pronounced in the axial direction, and double-sided detonation can increase the blast load in the radial direction by up to 60%.

Shi et al. [10] numerically investigates the interaction of blast waves with individual structural columns and the effect of this interaction on the loads acting on the column. The effects of scaled distance, column stiffness, mass ratio and column geometry on blast loads were investigated by parametric analysis performed using AUTODYN 3D software. The study shows that existing empirical formulas significantly overestimate the loads on individual columns because they neglect the effects of wave diffraction and pressure relief. It was found that the column dimensions and geometry are determinants of the interaction. As a result, new formulas were developed to estimate the blast pressure and impulse on individual columns

Chester et al. [11], this study presents a comparative analysis of five different commercial software programs (Autodyn, blastFoam, EMBlast, ProSAir and Viper::Blast) used for far-field estimation of blast loads. The software programs were used to simulate two different TNT blast scenarios against a reflective target and the results were compared with each other and with experimental data. The findings show that there are significant differences of up to 50% in peak overpressure estimates and 15% in specific impulse between the software programs. Simulation times can vary up to 600 times. The study highlights that the choice of software can directly affect the results of blast-resistant structure design.

Sha et al. [12] numerically investigate the attenuation of blast waves by obstacles with different geometries in this study. The interaction processes of blast waves passing through four different obstacles (rectangle, isosceles triangle and two different right triangles) were analyzed using the 5th order WENO scheme and the immersed boundary method. The findings reveal that the geometry of the obstacle is decisive on the attenuation performance. In particular, it was found that the right-angled triangle with its vertical surface facing the blast wave attenuates the intensity of the incoming shock wave the fastest and most effectively compared to other geometries. The study shows that the shape of the obstacle directly affects the attenuation mechanism by governing the interaction with the reflected and propagating waves.

Guo et al. [13] experimentally and numerically investigate the effects of internal explosions on a reinforced concrete shear wall (RCSW) structure. In the study, a three-stage TNT explosion was applied to a 1/3-scale structural subsystem and the results were verified with a finite element model developed with LS-DYNA. The main findings show that the energy released by the enveloping effect of the enclosed volume explosion is approximately 1.95 times higher than that of the free air explosion (FAE). As a result, the peak overpressures acting on the structural walls are 1.79 times higher and the total blast loads are 11.13 times higher.

Sugiyama et al. [14] conducted two-dimensional explosion experiments to investigate the interaction between a blast wave and a sand dune and the mitigation effect of sand on the explosion. In the experiments, a detonating cord was placed inside the sand dunes in the shape of a triangular prism. The findings show that the interaction of the blast wave with the sand/air interface causes multiple peaks in the blast wave due to successive transmissions at the interface. It was also found that the increase in the sand mass further reduces the peak overpressure and positive impulse and increases the attenuation effect.

When literature studies are examined, it is seen that free open air explosions are simulated with AUTODYN and similar applications. In addition, the interaction of blast waves with the environment has been an important study subject. Numerical studies have been verified with experimental and empirical data and it has been determined that there are some differences. The geometric shape, location, type and assumptions of the explosive have caused these differences, but the similarity in the pressure-time graph behavior and impulse amounts resulting from the explosion have emerged as important parameters in the verification of the numerical study. This study examines the interaction of blast waves with barricades in detail. The study was carried out in the AUTODYN application with numerical analyses based on experimental data. Within the scope of the study, the four most commonly used different barricade types were examined. It has been determined that there are not enough sources in the literature regarding the examination of the effectiveness of barricades against blast pressure, and the examination of the relationship between blast pressures and barricades, which are widely used and made against particles scattered around as a result of the explosion, has been provided.

Although the protection of barricades against explosion effects is known, the amount of protection and behavior can vary depending on many situations. One of the most important elements that trigger this interaction is the geometric shape of the barricade. In the scope of this study, studies were carried out with commonly used barricade types. Soil barricades formed with soil piles, barricades with one side reinforced concrete and the other side reinforced concrete wall and single reinforced concrete wall type barricades were examined in the scope of this study. Economic, ease of construction and terrain conditions can play a role in the selection of barricades.

One of the important functions of barricades is to provide protection against high-velocity, low-angle fragments. The distance of the barricade, which has sufficient dimensions to prevent the scattered fragments, to the protection area is not important. When it comes to preventing the explosion pressure, there is no definite information about the protection capability. It is mentioned that it will provide some reduction in the amount of pressure [14,15]. The reason for these descriptions is that the type of barricade and how far it is placed play an important role in protecting from the explosion pressure. Since the explosion pressure wave cannot be completely blocked by a standard barricade, some of the pressure can pass behind the barricade. This uncertainty constitutes the main idea of this study. In order to understand this situation, AUTODYN 2D numerical analyses, which were verified by experimental studies, were conducted

2. MATERIAL AND METHODS

2.1. General Approach in Numerical Modeling

In this study, numerical analysis was performed using the AUTODYN 2D computer program. The verification part of the analysis was the data obtained from the experiment conducted by Xu et al. [16]. Within the scope of the experimental study, 1 ton TNT equivalent explosive was used and the open air explosion pressure - time graph at 13m distance was obtained. That experimental environment was simulated within the scope of this study and the results were compared. The material models used in this analysis are shared as Table 1.1 and Table 1.2.

Material properties of Air:

Table 1: Material properties of air [17].

Material	Air
Equation of State	Ideal Gas
Rreference Density	1.225E-03[g/cm3]
Gamma	1.4
Adiabatic Constant	0
Pressure Shift	0 [kPa]
Reference Temperature	288.2 [K]
Specific Heat	717.6 [J/kgK]
Thermal Conductivity	0 [J/mKs]

Material properties of Explosive:

Table 2: Material properties of explosive [18].

Material	TNT
Equation of State	JWL
Reference Density	1.630 [g/cm3]
Parameter A	3.7377E+08 [kPa]
Parameter B	3747100E+06 [kPa]
Parameter R1	4.15
Parameter R2	0.9
Parameter W	0.35
C-J Detonation Velocity	6.9300E+03 [m/s]
C-J Energy / Unit Volume	6E+06 [kJ/m3]
C-J Pressure	2.1E+07 [kPa]

2.2. Theoretical Fundamentals of Numerical Modeling

In numerical analysis, hydro codes and equation of state (EOS) approaches were used to simulate the explosion. These approaches were used to simulate the propagation of explosion waves and their interaction with the environment.

2.2.1. Hydrocodes

In the numerical model, materials are defined as higher order differential equations, and the resolution of their relationships with each other is solved by complex mathematical equations. These analyzes are made with different methods for different material types. Two common methods used among these are the Euler and Lagrangian approximations. These two approaches have advantages in themselves and give more accurate results than material types.

The Euler approach defines a specific area and observes the materials entering, exiting and interacting within the area. It analyzes the properties of substances flowing through fixed cells in the region whose boundaries do not change. One of the situations that best describes this approach can be said as the observer watching the water flowing in the river on the river bank.

The Lagrangian approach, on the other hand, is almost the opposite of the Euler approach. While explaining the Lagrangian approach, it can be thought of as dropping a drop of paint into a glass filled with clear water and following this paint. In this approach, this time, the object itself is monitored, not a specific area. During this observation, the observed object can sometimes change shape and place [19].

Both methods have their strengths. The Euler method is effective in studying the behavior of fluid flow and highly deformed butt solids. Lagrange, on the other hand, is effectively used to examine the effects of the materials attached to each other while deforming. In explosion modeling, it is necessary to run both approaches together. While the floor and walls are modeled with Lagrange, the explosive that will cause pressure waves to propagate in air and air is modeled as Euler. Thanks to the Euler and Lagrange interaction, it is aimed to monitor the diffraction, flow and behavior of the detonation wave.

2.2.2. Equation of State EOS

It is an approach that provides the relationship of parameters such as pressure, density, internal energy in matter. Shape-phase changes and thermodynamic processes in matter are expressed with equations created with these parameters. There are different equations of state for different substances and phases. Jones - Wilkins-Lee (JWL) equation of state is used for explosive in situations where explosion environments are simulated. Ideal Gas Equation is used as the equation of state of air. The equation of state that reveals the effects of the shock created by the explosion effect on the material is the Shock State Equation.

The JWL Equation of State is used to model the phase changes of explosives. Explosive material detonates at the level of microseconds, and with a very rapid chemical reaction, it releases very high energy from the state it is in and produces products after the explosion. Modeling such rapid expansion states uses the JWL Equation of State.

Another equation of state is the Ideal Gas Equation of State, which is used in modeling air. The approach of this equation of state is based on the preserved harmony of pressure, volume and temperature in the gas. This conservation can be considered valid for all gases. Pressure shift is also used for small pressure losses that may occur in the model used.

In the Shock State Equation, the propagation of the shock wave on the material exposed to the shock effects can be modeled [18].

2.2.3. Validasyon

The numerical analysis environment is shared as Figure 1. The Remapping method was used to ensure that the analysis was completed more accurately and in a shorter time. The numerical analysis environment used for the explosive sub-model that enables remapping is shared as Figure 2. The global explosion event were solved with 1D analysis, and this solution was transferred with remapping method to the main numerical analysis environment [19].

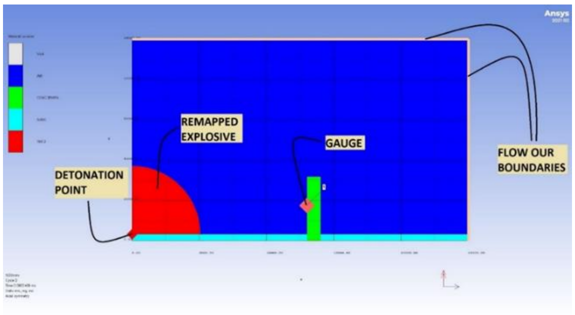

Figure 1: Validated numerical analysis model.

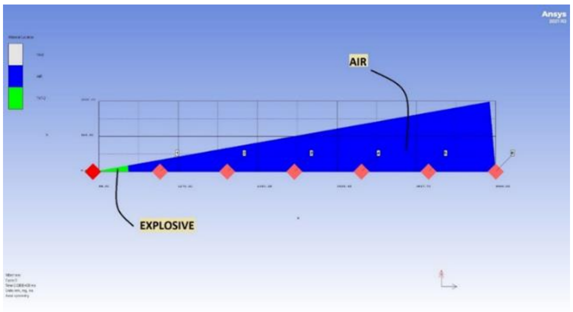

Figure 2: Explosive remapping submodel.

In the AUTODYN 2D numerical analysis created within the scope of this study, the explosion pressure results were compared with the quantities and distances in the experimental study of Xu et al. [16]. The results obtained with the numerical analysis and the experimental study results are shared in Figure 3.

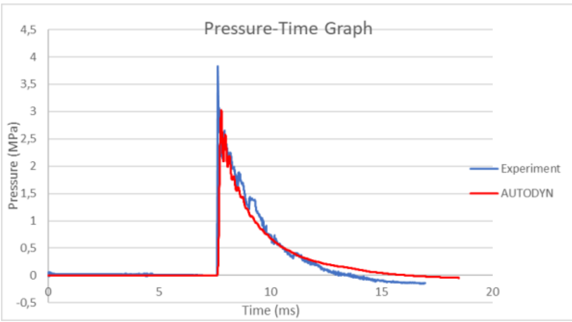

Figure 3: Pressure-Time graph comparing experimental [16] and numerical model results.

Differences between the environmental conditions in the experimental environment and the idealized analysis environments are inevitable. Furthermore, the mesh size and number, which determine the analysis size, affect the analysis results. Optimizing the analysis results is crucial. Using a 20 mm mesh size in the validated analysis environment yielded adequate results.

When the experimental data is examined with the validation numerical analysis environment, it is understood that the obtained data and behavior are quite similar. After this verification, the behavior behind the barricades was examined after the interaction of the explosion pressure with the barricades.

3. NUMERICAL ANALYSIS STUDY AND RESULTS

In the numerical analyses conducted in this study, different types of barricades were examined. These examined barricade types are the most common and are shared in Figure 4.

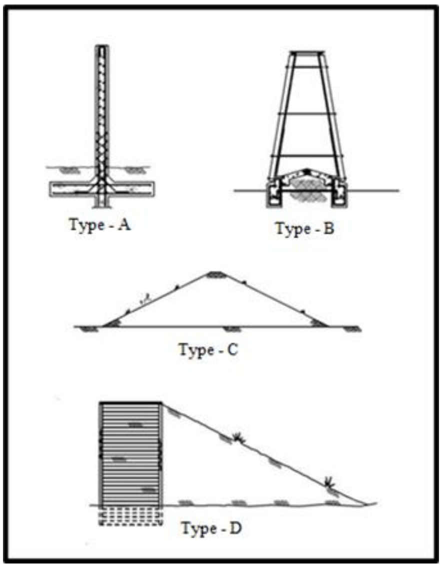

Figure 4: Common barricade [21].

In order to model the analysis environment correctly, the analysis was carried out in an air environment of 15m height and 25m length. In order to model the environment as open air, the environment boundaries were determined as flow out. In order to make the necessary readings, ten sensors were determined with 1 meter intervals starting from 16 meters away from the explosive and pressure-time readings were obtained.

3.1. Analysis of Results in Non-Barricaded and Barricaded Environments

In order to understand the effectiveness of the barricades, the situation without a barricade needs to be determined. This situation is modeled in the numerical analysis environment and the results are shown in Figure-5. The results in this analysis show that, as expected, the peak pressure decreases as the distance increases.

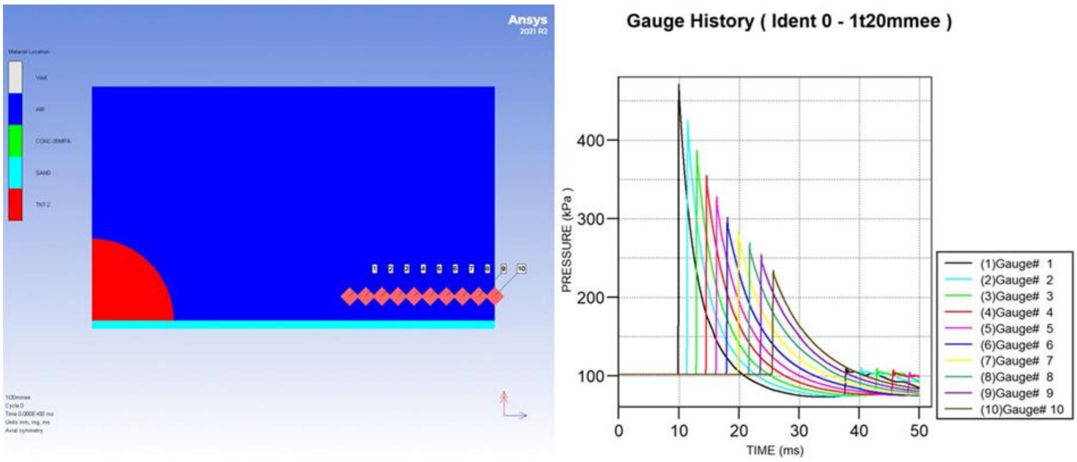

Figure 5: Unbarricated model and pressure time result graphs.

The barricades were included in the same explosion environment and the analyses were renewed. Four different barricades were determined and included in the analysis. The reinforced concrete flat wall was named Type-A and was conducted with the analysis code “1t20mmcc”. The Type-B barricade was determined as a reinforced concrete wall with the explosive side perpendicular to the ground and the protection side as sloping soil and was referred to with the analysis code “1t20mmcs”. Type-C type barricade was selected as sloping soil on the explosive side and reinforced concrete wall perpendicular to the ground on the protection side, and “1t20mmsc” analysis code was used. The soil barricade with two slopes was named Type-D and the analysis code was named “1t20mmss”. The analysis code of the barricade-free environment was determined as “1t20mmee”. The analysis environments and the obtained results are shared as Figures 6-7-8-9. Unlike the pressures read in the barricade-free environment, it is observed that double peak pressure occurs especially in the parts close to the barricade in barricaded environments.

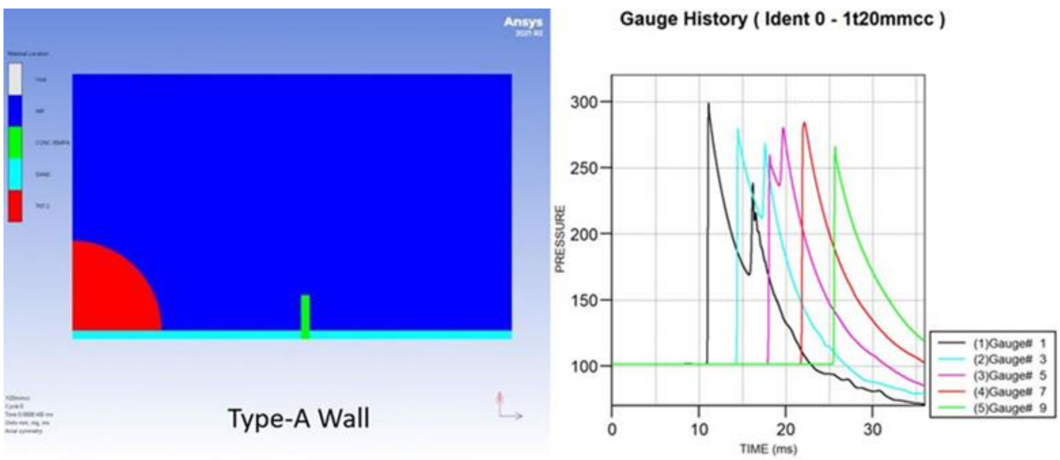

Figure 6: Type-A Barricaded Model and Pressure (kPa) versus Time (ms) result graphs.

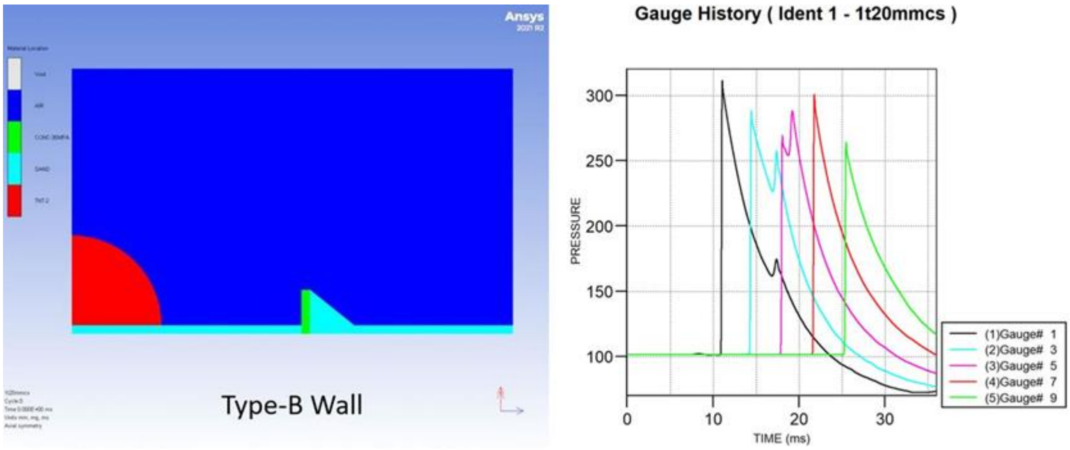

Figure 7: Type-B Barricaded Model and Pressure (kPa) versus Time (ms) result graphs.

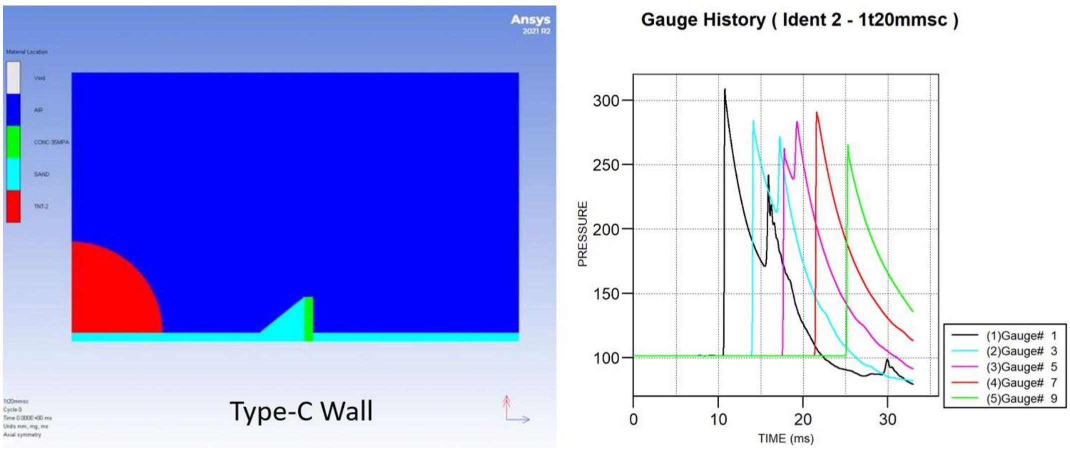

Figure 8: Type-C Barricaded Model and Pressure (kPa) versus Time (ms) result graphs.

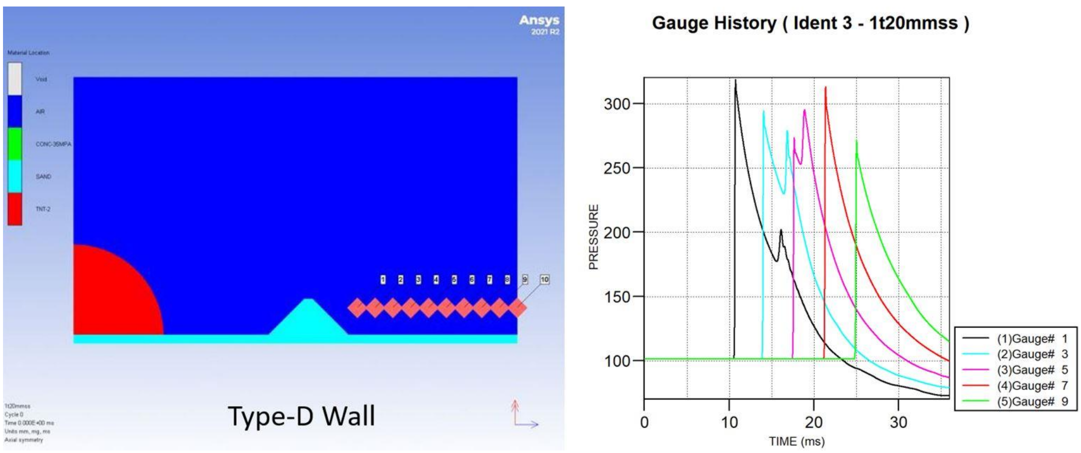

Figure 9: Type-D Barricaded Model and Pressure (kPa) versus Time (ms) result graphs.

In the analysis of results after barricades, it is seen that there is a double peak pressure in the readings close to the barricade. This is caused by the diffraction of the pressure waves affecting the barricade and their interaction with the ground, causing a Mach wave-like formation. Figure 10 shows the development that causes this situation. It is noteworthy that the common feature of the types that create double peak pressure is that the protection side is in the form of a wall perpendicular to the ground. It is understood that the second peak pressure occurs when the waves passing over the barricade suddenly turn towards the ground and a Mach wave-like formation occurs here.

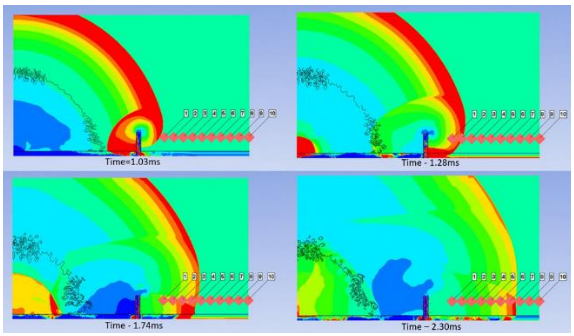

Figure 10: Pressure wave propagation over time.

Compared to the unbarricaded environment, although the amount of explosion peak pressure in areas close to the barricade has decreased, the protection zone exposed to consecutive explosion effects originating from double peak pressure. This behavior is not observed in an environment without barricades. The effectiveness of the Mach wave is most clearly seen here and reveals the necessity of positioning the barricade in the right place. It is observed that the pressure wave interaction formation experiences some changes according to the barricade types and the differences that occur decrease to a minimum as the distance to the explosion point increases.

The pressure-time graphs showing the situation developing compared to the unbarricaded situation as the distance increases are shared in Figure-11. Very similar explosion pressure relations are observed with open air pressure at a certain distance. As seen in Table 3, after a certain distance in a barrier-free environment, the peak pressure decreases more rapidly compared to a barricaded environment and falls below the peak pressure values of barricaded environments. The pressure measured in all barricaded environments after 21 meters at the explosion point contains higher pressure than the unbarricaded and other barricaded environments. Impulse is an important parameter that determines the damage formation. In Figure-12, impulse values formed at different distances are given comparatively according to wall types. In the measurements made in places close to the wall, it is seen that the pick pressure and the impulse value is higher compared to the case without the wall, and the measurements show that the Type-4 wall cannot provide effectiveness against impulse as the distance from the explosion point increases, and even causes a slight increase in impulse compared to the case without barricades in the area away from the explosion due to the Mach wave formed as a result of the interaction with the pressure wave. This result reveals how important design is according to the situation. In order to stay on the safe side, it is seen that designing only according to free air empirical pressure values as if there were no barricades may not be sufficient for barricaded situations.

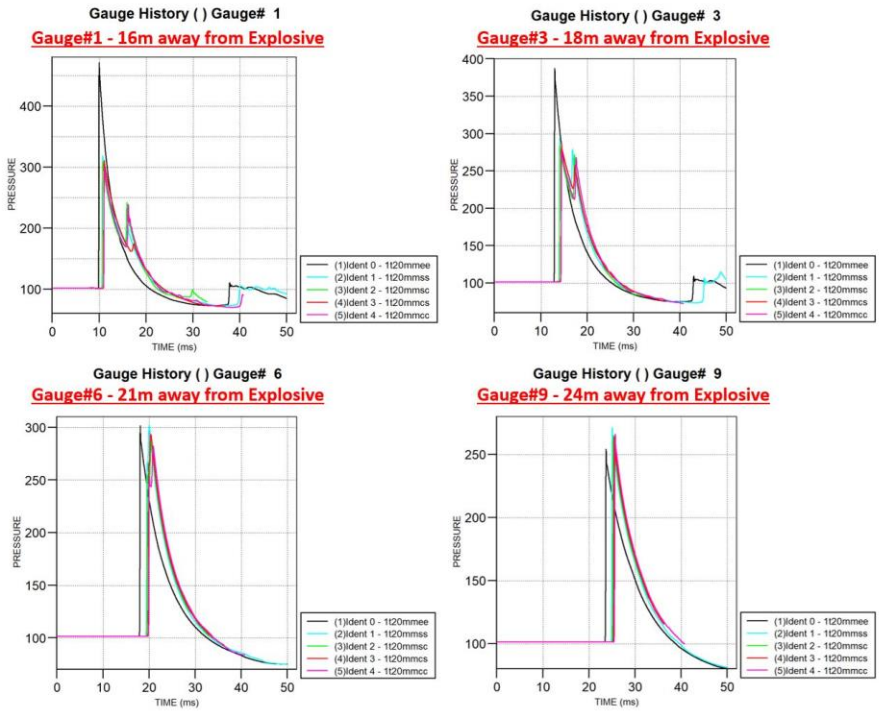

Figure 11: Comparison graphs of pressure (kpa) vs. Time (ms) values of non-barricaded and barricaded environments.

Table 4: Comparison of peak pressure values of non-barricaded and barricaded environments according to explosive distances.

Barricade Type	**Pick Pressure (kPa) at 16m**	**Pick Pressure (kPa) at 18m**	**Pick Pressure (kPa) at 21m**	**Pick Pressure (kPa) at 24m**
Unbarricaded	470.78	386.98	301.40	253.92
Type-A	298.80	279.17	282.16	265.93
Type-B	311.19	288.22	293.34	263.84
Type-C	308.67	284.15	285.27	265.20
Type-D	318.31	294.19	301.95	271.31

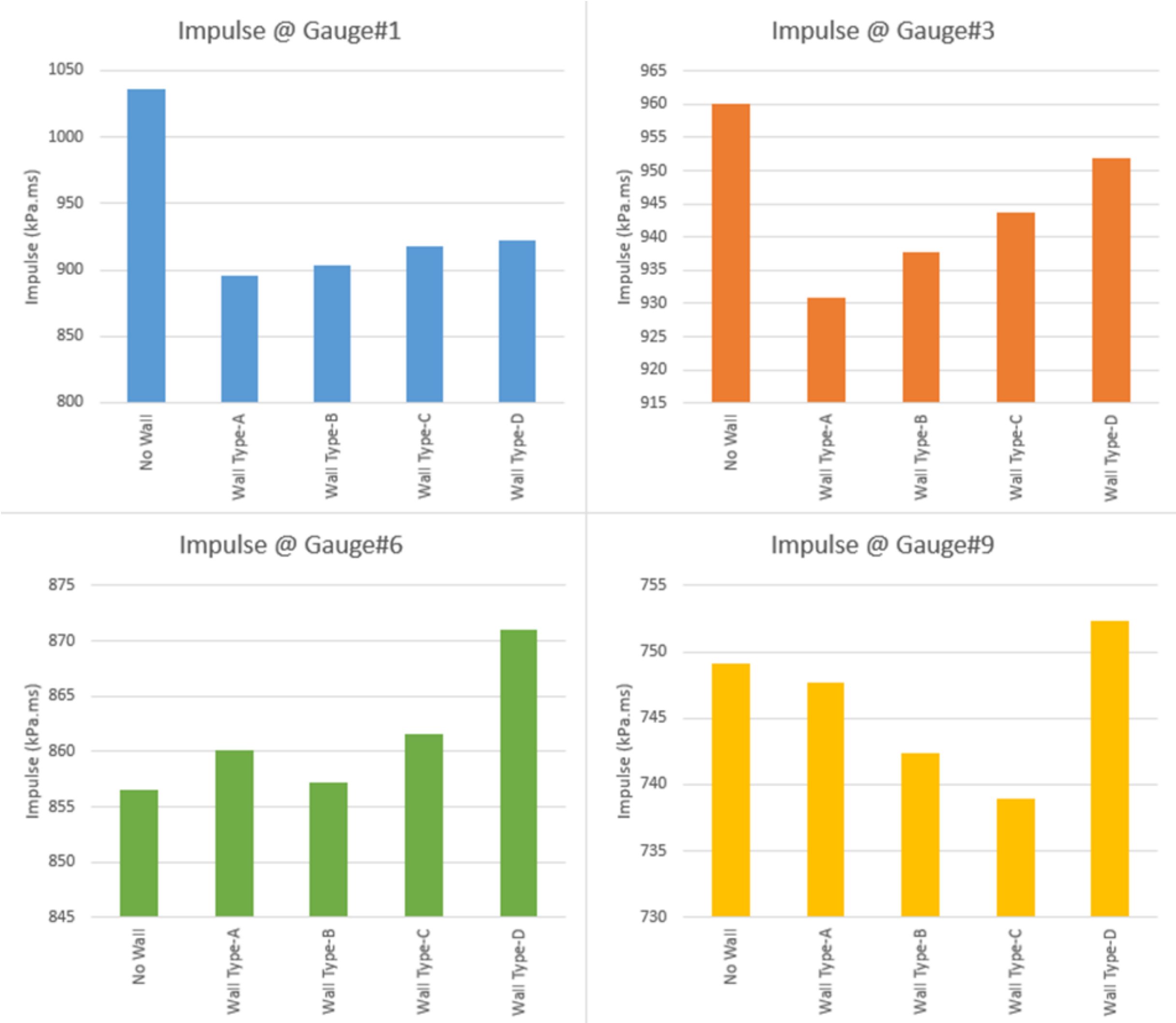

Figure 12: Comparison graphs of Impulse values of non-barricaded and barricaded environments.

4. CONCLUSIONS

In this study where the effects of explosion pressure are examined, the role of barricades in pressure distribution is aimed to be understood. When the environment without barricades is compared with the environment with barricades, it is understood that the distribution behavior and amount of pressure change. This change varies slightly across different barricade types. It is observed that double peak pressure occurs in the barricades and this causes the impulse value to increase. Although the data obtained from the unbarricaded and barricaded environments overlap as the distance increases, the Mach wave effects resulting from the interaction of the barricades with the ground have emerged as a matter that needs to be carefully examined. It has been observed that local pressure-intensified areas have formed, and it has become necessary to carefully evaluate the design of the structures to be built in these areas. In order to be aware of such formations and to be able to detect this situation, the importance of positioning the barricades with approaches similar to this study has been revealed. As a result of this study, the importance of making the barricade design specific to the situation and evaluating the precaution in the protection zone according to the situation is revealed. The issue of how the change in the barricade length affects this situation is considered a subject worth studying. The effects of different types of barricade geometries are also considered to be valuable topics to study.

Wall Type-D may appear disadvantageous in terms of size, it stands out as the most prominent type when viewed from a performance perspective. The necessity of situational analysis and interaction analysis, particularly Mach wave effects, is a key outcome of this study

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AUTHOR CONTRIBUTIONS

Melih YILDIZ: Conceptual Design, Methodology, Literature review, Analysis Evaluation, Writing.

Murat ŞAHİN: Conceptual Design, Methodology, Data Analytics.

CONFLICTS OF INTEREST

The authors have no competing interests to declare.

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