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Empirical Attenuation Law for Air Blast Waves Due to the Detonation of Explosives Outdoors

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Abstract: The detonation of explosives in the open air was studied, analyzing different amounts of explosives detonated at different distances, monitoring the overpressure or air blast wave generated with the aim of determining a model, which allows to establish safety zones. A series of tests measuring the air wave with different loads and sensors placed at various distances from the origin of the explosion were carried out. The work was focused on designing full-scale trials that allowed to develop a predictive empirical method based on the calculation model of the equivalent mass of TNT. A total of 18 different gelatinous dynamite charges, placing the sensor at six different distances from the origin of the explosion, produced a total of 90 tests measuring the air wave produced by the detonation of gelatinous dynamite. Later, the outdoor detonation of 10 TNT explosive charges was analyzed to extend the model and improve its scope. With all this, it has been possible to develop a predictive model that allows assessing the overpressure generated by the detonation of a TNT-equivalent explosive charge. The results are useful to predict the air blast wave in common open-air blasts, such as those carried out with shaped charges to demolish metallic structures. On the other hand, the results are also useful to determine the air blast wave overpressure in the case of large explosive charges detonated in the open air, such as accidental explosive detonation or terrorist bombs. It is important to point out the relevance of the results achieved after the detonation of large explosive charges (more than 80 kg) simulating a type of bomb frequently used by terrorists. Reproducing the explosion on a real scale, the results are fully representative of the overpressure produced by an explosion of these characteristics without the need of extrapolating the results of tests with small loads. In addition, the detonation was carried out with TNT, which can serve as a standard to compare with any other type of explosive.

Keywords: detonation; TNT; dynamite; air blast wave; overpressure

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1. Introduction

1.1. Air Blast Wave

An explosion is a physical phenomenon in which there is a sudden, very rapid release of energy. The phenomenon lasts only some milliseconds, and it results in the production of gas with very high temperature and pressure. During detonation, the hot gases that are produced expand in order to occupy the available space, leading to wave-type propagation through space that is transmitted spherically through an unbounded surrounding medium. Along with the produced gases, the air around the blast (for air blasts) also expands, and its molecules pile up, resulting in what is known as a blast wave and shock front. The blast wave contains a large part of the energy that was released during detonation and moves faster than the speed of sound [1].

This shock wave is characterized by an abrupt pressure rise followed by a relatively slow decrease to a value below atmospheric pressure and with a subsequent return to the positive value [1,2]. This phenomenon, which initially takes a few milliseconds, depends on the explosive mass and the distance to the initiation of the explosion. Subsequently, this waveform derived in a series of damped oscillations.

The study of the air wave produced by the detonation of explosives in the open air inevitably requires analyzing different controlled detonations and measuring the different parameters that characterize the air wave. This experimental level is not at all easy in the civil sphere, since the detonation of explosive substances involves having the availability of both the explosive and the initiator and the appropriate place to carry out the different detonations without affecting the surrounding environment—people, buildings, and communication ways.

The most characteristic effect of an explosion is the sudden increase in pressure that happens in the surrounding air, which propagates in the form of a spherical wave in all directions. The shape, characteristics, and magnitude of the wave depend on the type of explosion, the environment, and the distance from the origin where it was generated.

If the explosion takes place at a point far from the ground, the blast wave expands spherically, and its characteristics (maximum overpressure, duration, impulse, arrival time, etc.) are known as open-air explosion parameters. If the explosion occurs in the vicinity of the ground or on it, the parameters are known as surface explosion. In the first, any point will be affected by two shock waves: first, the incident one from the explosion and then the one reflected from the ground. In the second, the reflection on the ground is linked to the incident wave from the point of explosion, forming a single practically hemispherical wave, whose amplitude, for the same mass of explosive, is considerably greater than in the first case, since the energy must be distributed only in one hemisphere.

1.2. Negative Effects of Air Blast Wave

The air blast wave is an undesirable side effect that occurs in any explosive detonation and consequently has to be studied. The study of the air blast wave due to explosive detonation has been carried out in the last decades from two points of view.

One is the safety point of view, and the other is the environmental impact. The air blast wave is studied from the safety point of view because it has a great destructive effect within a radius that depends on the amount of explosive detonated.

During the second half of the 20th century, a considerable number of experimental and theoretical studies were conducted to understand the effects of blast on buildings and structures [3–7]. The aim was first to study the behavior of air blast waves including the determination of their characteristics and then to investigate the dominant factors influencing the incident waves. Another objective was to investigate the response of the building structure to blast loads [8–13].

The damage caused by the air waves on the structures depends on the overpressure, the impulse, and the formation of projectiles. The level of severity is also influenced by the orientation with respect to the direction of advance of the wave, the geometry of the structure (height/length ratio), and the construction materials. For emergency planning, it is interesting to consider inhabited buildings, due to the greater severity of the consequences.

When a shock wave reaches a structure, it is reflected, with an overpressure at least double that of the incident wave. The wave continues its propagation, reaching a moment in which the entire structure is encompassed by the wave. The explosions produced on the surface cause practically horizontal loads on the structures that they find in their path (except on the roof).

If the structure is small, with few openings, the load results in a homogeneous compression of it; if the structure is large, the load will be markedly different at the front and at the rear, with a greater potential for damage. The existence of openings or the breakage of some part of the structure will result in the homogenization of the pressure between the interior and the exterior of the structure. The calculation of the loads on a structure is carried out by combining the incident pressure and the dynamic pressure and their duration.

Actually, the response of a structure depends not only on the incident overpressure but also on the impulse (which takes into account the duration of the pressure pulse).

In the case of blasting in which the explosive is confined, it generates an air wave with a large proportion of low frequencies that can induce vibrations in buildings, although they are not heard because they are infrasonic. In any case, the effects of the air wave produced by a confined explosive are rarely harmful except in remote cases of glass breakage.

On the other hand, the air blast wave has been extensively studied from the environmental protection point of view. The air blast wave, even of a small intensity, can produce negative effects near the blasting areas. It is very typical of blasting related to mining (quarries or open-pit mines) or civil works (excavation or demolition). For example, the air blast wave can negatively influence the wildlife, which is critical in the case of protected animal species. In the same way, the air blast wave can produce different negative effects on population, from complaints of the neighbors of a village, to small damages to buildings, such as glass breakage or displacement of some tiles on the roof.

1.3. Empirical Prediction Models

Because of the importance of assessing the magnitude of the air blast wave, a lot of prediction models to determine explosion parameters, mainly overpressure, have been developed. These can be based on empirical (or analytical), semiempirical or numerical methods. Empirical methods are essentially correlations with experimental data. Most of these approaches are limited by the range of experiments carried out. The accuracy of all empirical correlations decreases with distance to the source of the explosion.

The use of empirical laws has been extensively studied and has been applied in various recommendations, mostly proposed by military authorities. After the first attempt due to Cranz [14], several methods were proposed [3–7], and due to the relevance of the topic recently, works about this topic have been published [15–17].

In the field of mining and civil engineering, several empirical models have also been proposed to estimate the magnitude of the air blast overpressure as for example [18–20].

In many cases, the air blast wave is given as a function of the scaled distance Z (in m/kg$^{1/3}$):

$$Z = \frac{R}{W^{1/3}} \tag{1}$$

R (m) is the distance from the explosion to the measurement point, and W (kg) is the amount of explosive detonated.

In order to be able to characterize the wave generated by any explosive substance and to be able to compare them with each other to assess their harmful effects after a detonation in the open air, it was important to establish a base explosive. The selected explosive was the Trinitrotoluene (TNT), which has well-known explosive properties. The TNT-equivalent mass is the mass of Trinitrotoluene (TNT) that would release an amount of energy equal to the explosive charge in question. If there is a mass W of a given explosive with an explosion heat Q, the equivalent TNT mass W_{eq} is:

$$W_{eq} = W\,\frac{Q}{Q_{eq}} \tag{2}$$

where Q_{eq} is the explosion heat of TNT Q_{eq} = 4520 kJ/kg.

The relationship (2) is widely accepted for blast-resistant design. It is proposed in documents taken as a reference or guides, such as UFC 3-340-02 [21] or EUR 2645EN [22], which allow to determine the incident and reflected overpressures and impulses of a spherical or hemispherical TNT explosion.

1.4. Research and Objectives

The detonation of explosives in the open air has been studied, analyzing amounts of explosive material and distances at which it detonates, with the aim of establishing safety zones, which implies previously determining the primary characteristic variables, as the air blast wave level.

Experimentation in this field presents great technical and economic difficulties, which is why most evaluations are carried out by extrapolation from small-scale experiences or from computer model results.

In the present study, two sets of full-scale tests were carried out. The first with small/medium explosive charges from 0.2 to 7 kg and the second trial with a large amount of explosive, from 25 to 84 kg (simulating terrorist bombs).

Two factors were taken into account that will fundamentally influence it: the explosive charge and the distance to the focus of the explosion.

To test the influence of these two factors, a campaign of air wave measurement tests was carried out with different charges and with sensors placed at different distances from the point of the explosion. With these tests, the intention was to obtain a model to predict the overpressure or magnitude of the air blast wave that is one of the factors influencing negatively on the environment and, in extreme cases, the main factor that affects the structures in outdoor detonations.

The works were focused on the design of a full-scale test procedure that would allow the development of a predictive empirical method based on the model for calculating the equivalent mass of TNT.

A total of 18 different Riodin explosive charges were formed, placing the sensor at six different distances from the focus of the explosion, with which a series of campaigns were carried out with a total of 90 air wave measurement tests produced by the detonation of gelatinous dynamite. With the results obtained, the pertinent adjustment of the TNT-equivalent mass calculation model was carried out, which was used to predict the effects generated by the air blast wave in the simulation processes of predefined scenarios.

Subsequently, the outdoor detonation of 10 TNT charges was analyzed in order to adjust the model and determine its range. Therefore, the results obtained in this work from the measurement of the air wave pressure peak in 100 full-scale tests are presented and analyzed, in which industrial and military explosives were detonated in the open air, without confinement, in different amounts, the highest that the environment allows without affecting people, communication routes, or buildings, which will conclude with the proposal of a calculation methodology based on the experience.

With all this, it was possible to develop a predictive model that allows assessing the overpressure generated by the detonation of a TNT-equivalent explosive charge. The results are useful to predict air blast waves in common open-air blasts, such as those carried out with shaped charges to demolish metallic structures. On the other hand, the results are also useful to determine the air blast wave overpressure in the case of large explosive charges detonated in the open air, such as accidental explosive detonation or terrorist bombs.

It is important to point out the relevance of the results achieved after the detonation of large explosive charges (more than 80 kg) simulating a type of bomb frequently used by terrorists. Reproducing the explosion on a real scale, the results are fully representative of the overpressure produced by an explosion of these characteristics without the need to extrapolate the results of tests with small loads. In addition, the detonation was carried out with TNT, which can serve as a standard to compare with any other type of explosive.

2. Materials and Methods

2.1. Equipment

For this research, the equipment used for data collection was an Instantel seismograph, Minimate Plus model, which has a channel for a microphone. It is a piece of equipment for monitoring vibrations and overpressure widely used in mining and civil works. Due to the wide range of acoustic pressure values measured, two different microphones were used for data collection. One is the microphone for air overpressure monitoring, which is supplied by default with the Minimate Plus seismograph; it is of the linear or A-weight type (see

Table 1). The other is a high-pressure microphone, which allows to measure pressure waves higher and can reach up to 69 kPa (Table 2).

Table 1. Instantel linear microphone characteristics used to measure air overpressure.

Scale type	Linear or A
Linear range	88 to 148 dB (500 Pa)
Linear resolution	0.25 Pa
Linear accuracy	+/−10% or +/−1 dB, whichever the higher, between 4 and 125 Hz
Linear frequency response	2 a 250 Hz between −3 dB points of roll off
A range	50–110 dBA
A resolution	0.1 dBA

Table 2. Instantel high-pressure microphone characteristics used to measure air overpressure.

Sensitivity	0.0233 V/kPa
Pressure range	0.0345 kPa to 69 kPa
Frequency response	5 to 1000 Hz

2.2. First Tests: Air Detonation of Dynamite Charges

The tests consisted of measuring the pressure wave or shock wave produced in a total of 90 explosions of different charges of a commercial explosive. These tests were carried out in the facilities of the Santa Bárbara Foundation, a public nonprofit foundation that works on training and R&D, always acting within the field of applied technology, safety, and technological progress. The foundation has several schools; one of them is located in the municipalities of Folgoso de la Ribera and Torre del Bierzo (León) where the trial was carried out.

For these first tests, gelatinous dynamite was used, specifically Riodin from the Maxam explosives manufacturer. The gum dynamite has a gelatinous consistency due to the greater amount of nitrogelatin in its composition (nitroglycerin/nitroglycol and nitrocellulose; >22%), and a predominant element is the ammonium nitrate. This mixture is even more energetic than nitroglycerin itself. This consistency of the explosive gives it, in general, an excellent resistance to water, as well as a high density. These characteristics, together with their high power and detonation speed, make them suitable for blasting rocks of a medium/high hardness, as well as for bottom loading holes and being essential for underwater blasting. Table 3 shows the main characteristics of Riodin. In order to obtain the amount of dynamite desired, cartridges of 26 mm and 32 mm in diameter (both 200 mm in length) were used in the tests.

Table 3. RIODIN main characteristics.

Packing density	1.45 g/cm^2
Detonation speed	6000 m/s
Heat of explosion at constant volume	4.09 MJ/kg
Gas volume produced	895 L/kg
Residual fume quality	Less than 2.27 L/100 g

To analyze the influence of the two more influencing factors, explosive dynamite charge and distance, a total of 90 airwave measurement tests were carried out. The distances and charges of Riodin-type gelatinous dynamite for each individual test are shown in Table 4.

Table 4. Riodin charge and distance for each test.

Num.	Distance (m)	Charge (kg)	Num.	Distance (m)	Charge (kg)	Num.	Distance (m)	Charge (kg)
1	25	0.238	**31**	25	3.571	**61**	15	3.571
2	25	0.714	**32**	25	4.286	**62**	25	3.571
3	25	1.190	**33**	25	4.762	**63**	40	3.571
4	25	1.190	**34**	25	5.476	**64**	50	3.571
5	25	1.190	**35**	25	5.952	**65**	75	3.571
6	25	2.381	**36**	25	6.667	**66**	15	4.762
7	25	3.571	**37**	25	7.143	**67**	15	5.952
8	25	4.762	**38**	75	2.381	**68**	15	7.143
9	25	5.952	**39**	75	1.190	**69**	15	5.952
10	25	7.121	**40**	75	0.714	**70**	15	4.762
11	25	4.762	**41**	50	2.381	**71**	10	3.571
12	10	2.381	**42**	50	1.190	**72**	10	2.381
13	10	3.571	**43**	50	0.714	**73**	10	1.190
14	15	3.571	**44**	40	2.381	**74**	10	4.762
15	15	4.762	**45**	40	1.190	**75**	25	2.381
16	15	5.952	**46**	40	0.714	**76**	25	3.571
17	25	2.381	**47**	25	2.381	**77**	10	4.762
18	25	2.381	**48**	25	1.190	**78**	10	1.190
19	25	3.571	**49**	25	0.714	**79**	15	1.667
20	25	3.571	**50**	15	2.381	**80**	15	2.381
21	25	4.762	**51**	15	1.190	**81**	25	1.905
22	25	4.762	**52**	15	0.714	**82**	25	3.095
23	25	3.550	**53**	25	0.714	**83**	25	3.571
24	25	0.238	**54**	25	1.190	**84**	25	3.571
25	25	0.476	**55**	25	2.381	**85**	25	4.762
26	25	0.714	**56**	15	1.667	**86**	25	5.714
27	25	1.190	**57**	25	1.905	**87**	25	5.714
28	25	1.905	**58**	40	1.905	**88**	25	5.714
29	25	2.381	**59**	50	1.905	**89**	25	5.714
30	25	3.095	**60**	75	1.905	**90**	25	4.286

2.3. Second Trial: Air Detonation of TNT Charges

The second tests consisted in measuring the pressure wave or shock wave produced in a total of 10 explosions with large charges of TNT.

The test was carried out at the "San Gregorio" Training Center, belonging to the Spanish Army (the General Military Academy, Zaragoza, Spain), which is located in the province of Zaragoza. It is the third largest training site in Europe.

The explosive chosen to be detonated in the open air was TNT. It is a light yellow, solid with a bitter taste, and it is less poisonous than other explosive substances. It has great chemical stability and very little sensitivity to shock. It is not affected by humidity, but by light, under whose action it acquires a dark color. Exposure to sunlight can cause sensitive alterations, and it burns without exploding, producing dense black smoke, unless stored in large quantities. It is the best of military explosives. It is used as a basic constituent of a multitude of explosive mixtures in the loading of projectiles, firecrackers, and multipliers. Its detonation speed is around 7000 m/s.

The mass and configuration of the explosive charge were typical of bombs used by terrorists. The handcrafted geometry of the TNT explosive is very characteristic (Table 5, Figure 1), which provides higher explosive characteristics than a normal configuration, since it deals with directed charges.

Table 5. TNT charge and distance for each test.

Num.	Distance (m)	TNT Charge (kg)
91	25	84
92	50	84
93	50	84
94	30	84
95	25	84
96	25	84
97	25	42
98	25	25
99	25	42
100	25	84

Figure 1. Directed charges of 42 kg of TNT.

Different resistant element designs were subjected to the action of the explosive detonated in the open air. These loads were raised from the ground using wooden supports, the distances at which the loads were separated from the structures between 1.5 and 3 m apart (see Figure 2).

Figure 2. Charge locations in front of the different structures.

Each of the structures was designed to withstand the effects of overpressure of a shock wave generated by the detonation of a TNT charge, directed at a given distance and different charges and separation distances depending on the structural element. The analysis of the behavior of these resistant elements is confidential, and it is out of the scope of the present work.

Nevertheless, we can say that all the results were not satisfactory or as expected. The main problem attributed by most of the calculators was the lack of full-scale tests in sufficient quantity to validate the air wave characterization models used to carry out the different designs. The importance of this air blast wave study can be then understood.

3. Results and Discussion

3.1. Results of the First Tests and Attenuation Law for the Air Overpressure Due to Common Blasts

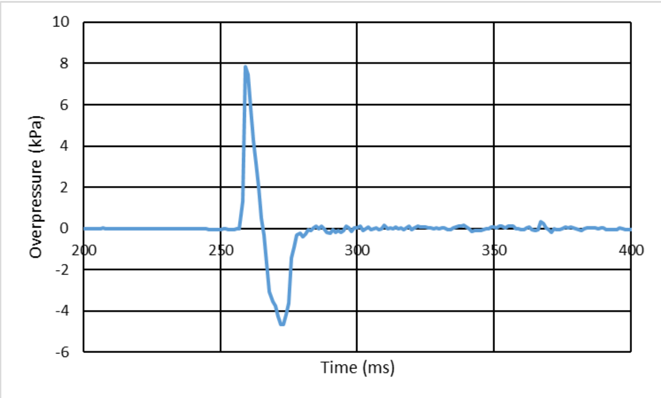
The detonation of the 90 charges of Riodin-type gelatinous dynamite located at different distances, detailed in Table 4, was carried out on different days. For each detonation, the value of the air overpressure of the detonation was measured in a straight line and was recorded without obstacles using the high-pressure microphone.

In order to analyze the air blast wave values measured in the full-scale tests, the variable scaled distance Z ($m/kg^{1/3}$) defined by Equation (1) was used. This variable includes the influence of the two independent variables that clearly affect the value of the detonation overpressure. The calculated scaled distance and the value of the air blast wave or air overpressure for each detonation are shown in Table 6.

Table 6. Values of scaled distances and air overpressure for each detonated charge.

N	Distance (m)	Charge (kg)	Scaled Distance ($m/kg^{1/3}$)	Overpressure (kPa)	N	Distance (m)	Charge (kg)	Scaled Distance ($m/kg^{1/3}$)	Overpressure (kPa)	N	Distance (m)	Charge (kg)	Scaled Distance ($m/kg^{1/3}$)	Overpressure (kPa)
1	25	0.238	40.35	2.84	**31**	25	2.571	16.36	9.85	**61**	15	3.571	9.81	16.80
2	25	0.714	27.95	4.70	**32**	25	4.286	15.39	10.50	**62**	25	3.571	16.36	12.10
3	25	1.190	23.59	5.95	**33**	25	4.762	14.86	11.40	**63**	40	3.571	26.17	5.91
4	25	1.190	23.59	5.95	**34**	25	5.476	14.18	11.50	**64**	50	3.571	32.17	5.12
5	25	1.190	23.59	6.57	**35**	25	5.952	13.79	13.20	**65**	75	3.571	49.07	2.73
6	25	2.381	18.72	9.79	**36**	25	6.667	13.28	10.50	**66**	15	4.762	8.92	21.90
7	25	3.571	16.36	11.40	**37**	25	7.143	12.98	14.30	**67**	15	5.952	8.28	16.40
8	25	4.762	14.86	11.60	**38**	75	2.381	56.17	2.63	**68**	15	7.143	7.79	20.20
9	25	5.952	13.79	14.90	**39**	75	1.190	70.77	1.80	**69**	15	5.952	8.28	26.10
10	25	7.121	12.99	11.50	**40**	75	0.714	83.9	1.42	**70**	15	4.762	8.92	16.30
11	25	4.762	14.86	12.30	**41**	50	2.381	37.44	3.63	**71**	10	3.571	6.54	23.90
12	10	2.381	7.49	24.96	**42**	50	1.190	47.18	2.73	**72**	10	2.381	7.49	27.10
13	10	6.571	6.54	24.10	**43**	50	0.714	55.93	2.07	**73**	10	1.190	9.44	23.40
14	15	3.571	9.81	21.12	**44**	40	2.381	29.96	5.15	**74**	10	4.762	5.94	32.20
15	15	4.762	8.92	22.86	**45**	40	1.190	37.74	3.53	**75**	25	2.381	18.72	10.20
16	15	5.952	8.28	26.54	**46**	40	0.714	44.75	2.73	**76**	25	3.571	16.36	12.90
17	25	2.381	18.72	7.85	**47**	25	2.381	18.72	10.10	**77**	10	4.762	5.94	32.04
18	25	2.381	18.72	9.58	**48**	25	1.190	23.59	6.98	**78**	10	1.190	9.44	21.14
19	25	3.571	16.36	9.30	**49**	25	0.714	27.97	5.32	**79**	15	1.667	16.65	14.17
20	25	3.571	16.36	10.10	**50**	15	2.381	11.23	17.80	**80**	15	2.381	11.23	16.01
21	25	4.762	14.86	12.10	**51**	15	1.190	14.15	13.70	**81**	25	1.905	20.17	9.44
22	25	4.762	14.86	8.47	**52**	15	0.714	16.78	9.65	**82**	25	3.095	17.15	11.20
23	25	3.550	16.39	10.70	**53**	25	0.714	27.97	5.32	**83**	25	3.571	16.36	12.50
24	25	0.238	40.34	2.46	**54**	25	1.190	23.59	7.09	**84**	25	3.571	16.36	12.40
25	25	0.476	32.01	3.67	**55**	25	2.381	18.72	9.06	**85**	25	4.762	14.86	15.60
26	25	0.714	27.97	4.50	**56**	15	1.667	12.65	14.50	**86**	25	5.714	13.98	15.00
27	25	1.190	23.59	6.46	**57**	25	1.905	20.17	8.30	**87**	25	5.714	13.98	16.00
28	25	1.905	20.17	7.40	**58**	40	1.905	32.27	5.05	**88**	25	5.714	13.98	16.60
29	25	2.381	18.72	8.71	**59**	50	1.905	40.34	3.60	**89**	25	5.714	13.98	15.90
30	25	3.095	17.15	9.16	**60**	75	1.905	60.50	1.76	**90**	25	4.286	15.39	13.90

All the cases are characterized by short overpressure pulses. To illustrate it, the overpressure records obtained in tests no. 17 (S_b = 7.85 kPa) and no. 37 (S_b = 14.3 kPa) are shown in Figure 3 (left and right, respectively). The duration of the positive phase is only a few milliseconds, 5–10 ms. They are in accordance with the results of recently published research [16], keeping in mind that in our case, the explosive charge is on the floor, and consequently the overpressure is approximately twice the overpressure measured by them.



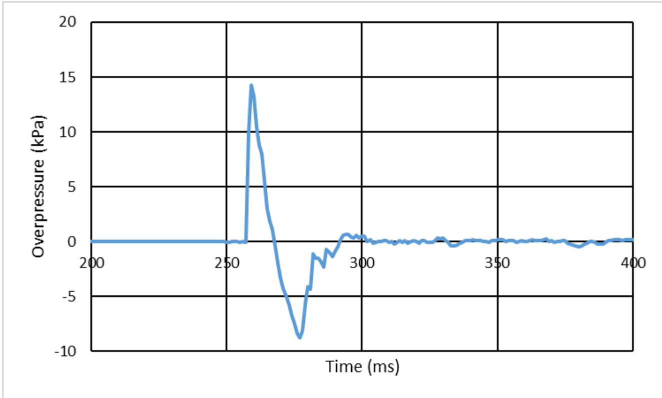


Figure 3. Air overpressure measured in tests no. 17 (**left**) and no. 37 (**right**).

The graph in Figure 4 was obtained by representing the overpressure measured at each detonation against the scaled distance in logarithmic scales. It is clear that there is a linear relationship between the log(S_b) and the log(Z), which means that there is a potential relationship between the variables S_b (kPa) and Z (m/kg$^{1/3}$). By applying logarithms and a least squares adjustment, the following relationship was found:

$$S_b = 309.33 \cdot Z^{-1.216} \tag{3}$$

with a high correlation coefficient r^2 = 0.96. This is in accordance with the first experiences in this field [10].

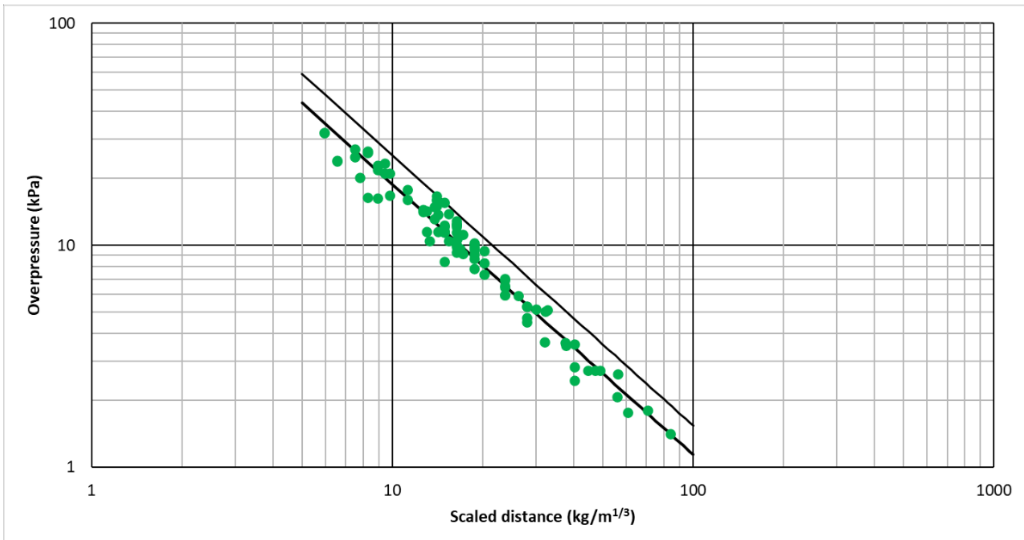


Figure 4. Air overpressure measured as a function of scaled distance with Riodin charges (dots are actual values while lower and upper lines correspond to Equation (3) and Equation (5) respectively).

On the other hand, the formula is quite similar to the prediction model proposed by the manufacturer of the explosive:

$$S_b = 322 \cdot W^{0.56} \cdot R^{-1.3} \quad (4)$$

although the latter gives results lower than the ones obtained from the experiences described here and it is useful only for Z >100.

In the last years, different relationship between air peak overpressure Sb and scaled distance Z, mainly polynomial, have been proposed by several authors [3–5]. We propose the exponential function for coherence with the analysis of air blast wave due to blasting in civil engineering with which this study is most related. On the other hand, it is a simple formula that only needs two empirical parameters. The relationship between the logarithm of the air overpressure log(S_b) and the logarithm of the scaled distance log(Z) is linear, and these two parameters can be deduced easily from field data by means of a linear regression. In the present study, the correlation coefficient found is high, r^2 = 96%, demonstrating that it is a sufficiently accurate approach for different analysis.

The point cloud and the regression line are represented in Figure 4. As can be deduced from the same figure, some actual values are higher than the predicted ones. Due to the fact that the aim of the research is safety, a coefficient can be used to assure that any predicted value is higher than the actual one with a given confidence level, i.e., 90% (the predicted value is higher than the actual one in more than 90% of the cases). By using the coefficient of 1.35, the predicted air overpressure fulfils this requirement. The expression deduced in this way is known as the attenuation law:

$$S_b = 417.59 \cdot Z^{-1.216} \quad (5)$$

Equation (4) corresponds to the lower line of the graph, while Equation (5) corresponds to the upper one.

With the values given by Formula (5), we have a predictive model that allows us to characterize the aerial wave generated by the detonation of Riodin-type gelatinous dynamite charges as a function of the distance to the detonation focus. It allows us to assess the overpressure generated by the detonation of a charge of this specific explosive and the possible effects on people or buildings that it will produce. Thus, protection and attenuation mechanisms are established and designed to greatly reduce the consequences of this detonation.

However, the reality is that explosive substances can be of a different nature and composition, not just gelatinous dynamites. For example, a typical blasting work, which produces high air overpressure, is the demolition of metallic structures with shaped charges (Figure 5). It is due to the fact that the explosive is not confined in a blast hole, but it detonates in the open air. In this case, the explosive is pentolite (Riocut), different from dynamite (Riodin), and then the deduced Formula (5) cannot be used directly.

So, in order to be able to characterize the wave generated by any explosive substance and to be able to compare them with each other to assess their harmful effects after a detonation in the open air, the equivalent TNT mass is used.

To apply this calculation method, it is necessary to know the heat of explosion, both of the TNT and of the explosive to be compared. The heat of explosion for TNT is 4520 kJ/kg, and from Table 3, there is a heat of explosion for this Riodin dynamite of 4090 kJ/kg. So, 1 kg of Riodin is equivalent to $1 \times 4090/4520 = 0.905$ kg of TNT. With these explosion heat values, the TNT equivalent of each charge used in the 90 detonations is determined, as well as the reduced distance for each of them with this resulting TNT-equivalent charge (Table 7).

The resulting values from Table 7 are shown in Figure 6 in which the measured overpressure is plotted against the TNT-equivalent scaled distance.

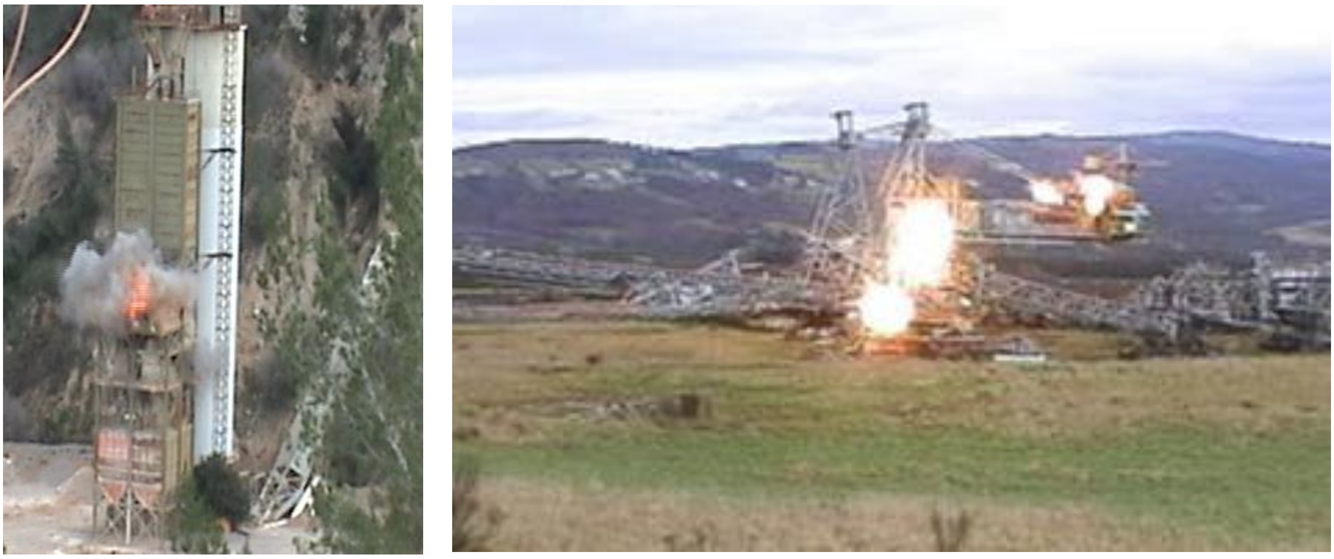


Figure 5. Demolition of metallic structures with shaped charges ((**left**) metallic silo; (**right**) large mining stacker).

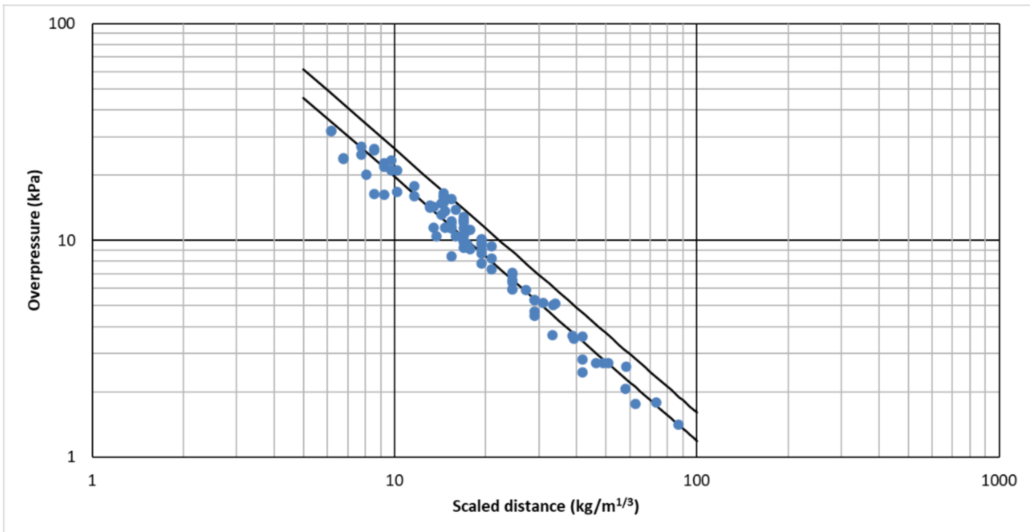


Figure 6. Overpressure measured as a function of scaled distance using the equivalent mass of TNT (dots are actual values while lower and upper lines correspond to Equations (6) and (7)).

Due to the proportionality between the Riodin and TNT explosion heats used, the expression deduced in this case by linear regression is similar to the previous one:

$$S_b = 322.13 \cdot Z^{-1.216} \quad (6)$$

where S_b is the overpressure generated by the wave in kPa, and Z is the reduced distance in m/kg$^{1/3}$. The correlation coefficient for this prediction model is also 96.06%.

By using the coefficient of 1.35, the predicted air overpressure will be higher than the actual one in more than 90% of the cases, and the formula represents the attenuation law of the air wave in the case of TNT explosive:

$$S_b = 434.87 \cdot Z^{-1.216} \quad (7)$$

Equation (6) corresponds to the lower line of the graph, while Equation (7) corresponds to the upper one.

Table 7. TNT-equivalent charge and scaled distance for each Riodin-detonated charge.

N	Distance (m)	Eq. TNT Charge (kg)	Scaled Distance (m/kg$^{1/3}$)	Overpressure (kPa)	N	Distance (m)	Eq. TNT Charge (kg)	Scaled Distance (m/kg$^{1/3}$)	Overpressure (kPa)	N	Distance (m)	Eq. TNT Charge (kg)	Scaled Distance (m/kg$^{1/3}$)	Overpressure (kPa)
1	25	0.215	41.70	2.84	**31**	25	3.232	16.91	9.85	**61**	15	3.232	10.15	16.80
2	25	0.646	28.91	4.70	**32**	25	3.878	15.91	10.50	**62**	25	3.232	16.91	12.10
3	25	1.077	24.39	5.95	**33**	25	4.309	15.36	11.40	**63**	40	3.232	27.06	5.91
4	25	1.077	24.39	5.95	**34**	25	4.955	14.66	11.50	**64**	50	3.232	33.82	5.12
5	25	1.077	24.39	6.57	**35**	25	5.386	14.26	13.20	**65**	75	3.232	50.73	2.73
6	25	2.154	19.36	9.79	**36**	25	6.032	13.73	10.50	**66**	15	4.309	9.22	21.90
7	25	3.232	16.91	11.40	**37**	25	6.463	13.42	14.30	**67**	15	5.386	8.56	16.40
8	25	4.309	15.36	11.60	**38**	75	2.154	58.07	2.63	**68**	15	6.463	8.05	20.20
9	25	5.386	14.26	14.90	**39**	75	1.077	73.16	1.80	**69**	15	5.386	8.56	26.10
10	25	6.444	13.43	11.50	**40**	75	0.646	86.74	1.42	**70**	15	4.309	9.22	16.30
11	25	4.309	15.36	12.30	**41**	50	2.154	38.71	3.63	**71**	10	3.232	6.76	23.90
12	10	2.154	7.74	24.96	**42**	50	1.077	48.78	2.73	**72**	10	2.154	7.74	27.10
13	10	2.331	6.76	24.10	**43**	50	0.646	57.83	2.07	**73**	10	1.077	9.76	23.40
14	15	3.231	10.15	21.12	**44**	40	2.154	30.37	5.15	**74**	10	4.309	6.15	32.20
15	15	4.309	9.22	22.86	**45**	40	1.077	39.02	3.53	**75**	25	2.154	19.36	10.20
16	15	5.386	8.56	26.54	**46**	40	0.646	46.26	2.73	**76**	25	3.232	16.91	12.90
17	25	2.154	19.36	7.85	**47**	25	2.154	19.36	10.10	**77**	10	4.309	6.15	32.04
18	25	2.154	19.36	9.58	**48**	25	1.077	24.39	6.98	**78**	10	1.077	9.76	21.14
19	25	3.232	16.91	9.30	**49**	25	0.646	28.91	5.32	**79**	15	1.508	13.08	14.17
20	25	3.232	16.91	10.10	**50**	15	2.154	11.61	17.80	**80**	15	2.154	11.61	16.01
21	25	4.309	15.36	12.10	**51**	15	1.077	14.63	13.70	**81**	25	1.724	20.85	9.44
22	25	4.309	15.36	8.47	**52**	15	0.646	17.35	9.65	**82**	25	2.801	17.74	11.20
23	25	3.212	16.94	10.70	**53**	25	0.646	28.91	5.32	**83**	25	3.232	16.91	12.50
24	25	0.215	41.7	2.46	**54**	25	1.077	24.39	7.09	**84**	25	3.232	16.91	12.40
25	25	0.431	33.1	3.67	**55**	25	2.154	19.36	9.06	**85**	25	4.309	15.36	15.60
26	25	0.646	28.91	4.50	**56**	15	1.508	13.08	14.50	**86**	25	5.171	14.46	15.00
27	25	1.077	24.39	6.46	**57**	25	1.724	20.85	8.30	**87**	25	5.171	14.46	16.00
28	25	1.724	20.85	7.40	**58**	40	1.724	33.36	5.05	**88**	25	5.171	14.46	16.60
29	25	2.154	19.36	8.71	**59**	50	1.724	41.7	3.60	**89**	25	5.171	14.46	15.90
30	25	2.801	17.74	9.16	**60**	75	1.724	62.55	1.76	**90**	25	3.878	15.91	13.90

3.2. Results of the Second Tests and Analysis of the Air Blast Wave Due to Bombs

Table 8 shows the parameters and results related to the ten explosions with a large amount of TNT explosive. Detonation number 91 was canceled because the microphone did not work properly.

Table 8. Values of scaled distances and air overpressure for each detonated TNT charge.

N	Distance (m)	TNT Charge (kg)	Scaled Distance ($m/kg^{1/3}$)	Overpressure (kPa)
91	25	84	5.71	-
92	50	84	11.42	16.00
93	50	84	11.42	21.90
94	30	84	6.85	45.30
95	25	84	5.71	63.80
96	25	84	5.71	57.60
97	25	42	7.19	36.30
98	25	25	8.55	33.00
99	25	42	7.19	57.00
100	25	84	5.71	54.10

In the case of detonation of TNT charges, two different behaviors can be seen. There is one test in which the air blast wave is moderate, and the shape of the overpressure pulse is similar to that described above. It is rather symmetrical, and the positive and negative parts are approximately of the same magnitude as can be seen in the overpressure record measured in test no. 92 (S_b = 16.0 kPa), Figure 7 (left).

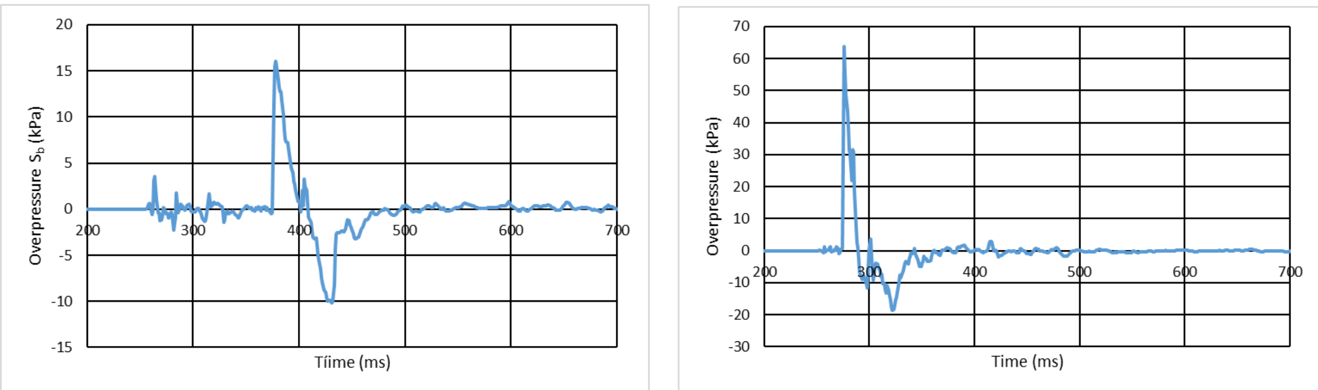


Figure 7. Air overpressure measured in tests no. 92 (**left**) and no. 95 (**right**).

Nevertheless, when the air blast wave is high, the shape of the pulse is equal to the ideal blast wave pressure with the positive part much higher than the negative one. On the other hand, the duration of the positive phase in these tests is significantly higher than in the others. For example, the overpressure measured in test no. 95 (S_b = 63.8 kPa) is shown in Figure 7 (right).

These overpressure results can be drawn together with the results obtained with the TNT explosive equivalent to Riodin dynamite. Then the graph of Figure 8 was obtained.

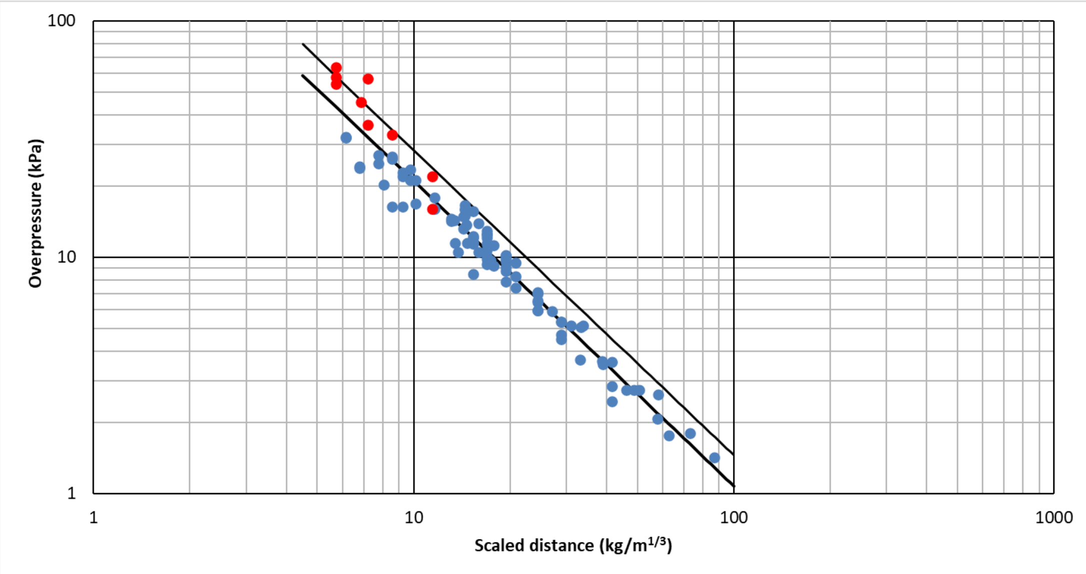


Figure 8. Overpressure measured as a function of scaled distance for the detonation of pure TNT and equivalent TNT (dots are actual values while lower and upper lines correspond to Equation (8) and Equation (9) respectively).

The expression derived from the data set is:

$$S_b = 396.27 \cdot Z^{-1.280} \tag{8}$$

With a correlation coefficient r^2 = 95.9%.

By using the safety coefficient 1.35, the predicted air overpressure will be higher than the actual one in more than 90% of the cases, and the attenuation law of the air wave in the case of TNT explosive is:

$$S_b = 534.96 \cdot Z^{-1.280} \tag{9}$$

Formula (9), or alternatively the graphic of Figure 6, is useful to predict air blast wave overpressure near the explosion even in the case of detonation of a large amount of explosive.

4. Conclusions

The peak pressure value of the air blast wave from a total of 100 records corresponding to the detonation of different explosive charges in the open air was analyzed. These records can be separated into two basic groups: records from open-air detonations of a gelatinous dynamite-type explosive and records from open-air detonations of a TNT-type explosive.

The most important result achieved was the definition of an air wave attenuation law, overpressure S_b as a function of the scaled distance Z, for the determination of the overpressure peak due to the detonation of explosive charges in the outdoors. The law is simpler than others since it only requires the determination of two empirical parameters that can be determined with a smaller number of samples.

The model predicts the peak value of the air blast wave S_b (kPa) from the detonation of a given or equivalent TNT explosive charge in the open air that relates to the value of such variable, S_b, with the scaled distance Z (m/kg$^{1/3}$):

$$S_b = 396.27 \cdot Z^{-1.280}$$

where $Z = R/W_{eq}{}^{1/3}$, that is, the distance R (m) divided by the cubic root of the equivalent TNT mass W_{eq} (kg).

By using a safety coefficient of 1.35, the predicted S_b is higher than actual S_b in more than 90% of the cases:

$$S_b = 534.96 \cdot Z^{-1.280}$$

It has been demonstrated that this law is valid in a wide range of the reduced distance, with Z varying between 5.71 and 86.74 $\mathrm{m/kg^{1/3}}$, and in a wide range of the air wave, with S_b between 1.42 and 63.8 kPa. In this way, the attenuation law is useful both for the prediction of the air blast wave due to the detonation of charges of a few kgs of explosives (such as the shaped charges used in civil works for the demolition of metallic structures) and for the prediction of the air wave in the case of the detonation of several tens of kgs of explosives (such as explosive detonations by accident or terrorist bombs).

The model proposed aims to serve as a basis for the design of protection and containment elements, but it is considered necessary to continue testing with full-scale explosives, in order to further limit other parameters involved in the propagation of the resulting wave of a detonation, tests that are difficult to carry out because they are of a destructive nature and because they are controlled materials for which there is authorization for consumption, qualification, and training.

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