Determination of the Danger Area under the Effects of the Explosive Shock Wave

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***Abstract*— Explosives detonation could cause a partial or total destruction of equipment and installations, which in some cases derives in technical staff fatality. The present study aims to define blast wave parameters for spherical explosive in outdoor detonation. To achieve this purpose, a total of 30 blast wave tests were developed in samples of 1kg, 3kg and 5 kg of TNT; the experimental results were compared with standards and handbooks of explosion protection in order to evaluate the damage produced by blast wave effect in equipment, installations and technical professionals. The results reflect a range of safe-zones that varies from 7 m to 300 m according to explosives magnitude, furthermore the results also show the distance at which blast wave provoke lethal injuries. Finally, this research will be applied in further experimental tests related to the controlled demolition of building structural elements, to maximize safety ranges and minimize equipment damage, injuries and fatalities in these events.**

***Index Terms*— TNT, shock wave, detonation, incident pressure, security zone**

I. INTRODUCTION

In recent decades, use of explosives has increased in both civil and military scope, on top of that, the operation of this type of materials presents a high probability of structure damage and staff fatalities [1]. To cope with this problem, global organizations and governmental entities have conducted studies about blast wave (i.e. sudden release of large energy amounts in a wave from) produced by explosives detonation (i.e accidentally or intentional cases) to determine infrastructure protection plans and safety standards optimization.

The safety parameters are fundamental aspects in detonation processes (i.e. plans and procedure of explosives work) this study aims to reduce the equipment and infrastructure damage, as well as injuries and fatalities of technician staff, due to explosives detonation processes. Similar researches worldwide have established safety parameters for explosives utilization, Manual [2] presents design methods based on experimental development, for protection of facilities intended to develop, test, produce, store, maintain, modify, inspect, demilitarize and destroy explosive materials; as well as, contribute in the process making decision and risk management in safe and effective way. On the other hand DoD [3] developed standards in order to maximize safety ranges for structures and technical staff that are exposed to explosives detonation. Additionally, it establishes processes about the exposure time to detonation effect, the lowest number of technical staff and compatible explosives to safe and efficient operations.

Longinow [4] proposed a regulation for infrastructure protection against blast wave, its covers planning, design, construction and evaluation for both existing and new building projects subjected to accidental or intentional explosions. Besides, it includes principles to establish threats, security levels, methodological analysis and tests for explosions.

DoD [3] and the International Center for Humanitarian Demining of Geneva [5] section II, detail shock wave effects induced by explosives detonation in infrastructure and technical operators in terms of damage and incidence pressure.

This research is based on empirical methods for explosive wave characterization according US Department of Defense [2], which was determine by experimental correlations provided by DoD [3] the technical manual of Kingery and Bulmash [6] which provides shock wave parameters in form of polynomial diagrams and shapes, Swisdak Jr [7] model that establishes the same parameters of Kingery and Bulmash [6] but in this case is used exponential equations, Henrych and Major [8] and Sadovsky [9] models show the polynomial shapes to establish the incidence pressure. Additionally, it was correlated with values established in the Demining [5] by Zipf and Cashdollar [10] and White, Jones [11]; as well as in the DoD [3] through the study conducted by Kinney and Graham [12] , reaching to define the impact and damage caused by the detonation based on shock wave destructive effects on infrastructure, filming equipment and technical personnel.

This research aims to define the security parameters, the optimal filming location and safety areas according to explosives magnitude in terms of incidence pressure, these parameters were validated through technical guides and manuals about protection against damage and destruction of infrastructure; morbidity and mortality in humans.

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II. CALCULATION METHODOLOGY

At the moment that an explosive is triggered a chemical reaction is generated which radially releases a large amount of heat and compressed gas with a supersonic speed (greater than 7000 m/s) that varies over time. The shape and magnitude of the shock wave depends on the quantity, position, geometry and type of explosive to use. This wave moves along space-time, as seen in Fig. 1.

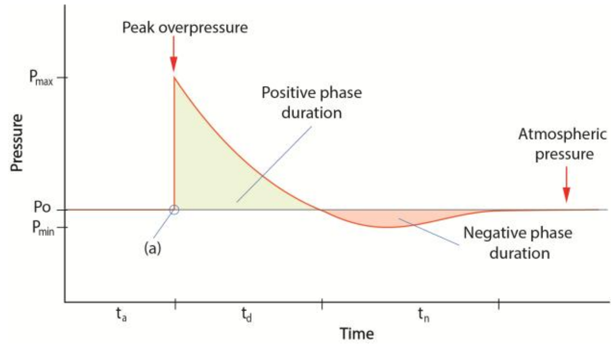

Figure 1. Pressure – time curve for a free air blast wave. Reference: Larcher [13]

To establish the parameters of the shock wave at a specific point (a) of its trajectory, it is necessary to determine the time (ta) at the moment in which the wave reaches that point, which is directly related to a sudden pressure change until attaining its maximum value (Pmax) also known as incidence pressure (P_I); as shown in Fig. 1 in the td interval (positive phase) this value decreases exponentially until atmospheric pressure (Po), while in (tn) interval (negative phase) the pressure decrease till minimum value (Pmin) to subsequently increase until it stabilizes in Po [13].To determine P_I, it is necessary to define the concept of scaled distance that is expressed by equation (1),

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

where, Z is the scaled distance in $m/kg^{1/3}$, R is the distance from the detonation point to the safe area in m; and W is the mass of the explosive in kg [14].

Henrych and Major [8] established equations (2), (3) and (4) for P_I in the intervals 0.05 <Z <0.3, 0.3 <Z <1 and 1 <Z <10, respectively.

$$P_I = \frac{14.072}{Z} + \frac{5.540}{Z^2} - \frac{0.357}{Z^3} + \frac{0.00635}{Z^4} [bar] \tag{2}$$

$$P_I = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3} [bar] \tag{3}$$

$$P_I = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.228}{Z^3} [bar] \tag{4}$$

Likewise, Sadovsky [9] experimentally determined equation (5), to obtain P_I.

$$P_I = \frac{0.085}{Z} + \frac{0.3}{Z^2} + \frac{0.8}{Z^3} [MPa] \tag{5}$$

On the other hand, Kingery and Bulmash [6] developed logarithmic and polynomial expressions (see equations 6 and 7) for the different parameters of the shock wave, whose constants are presented in Table I.

$$U = K_0 + K_1 * \log(Z) \tag{6}$$

$$P_I = 10^{C_0 + C_1 * U + C_2 U^2 + \ldots + C_N U^N} \tag{7}$$

Derived from the research of Kingery and Bulmash [6], Swisdak Jr [7] proposed a refined exponential type model (see equation 8) that allows obtaining P_I using constants (see Table II).

$$P_I = e^{A + B*\ln(Z) + C*\ln(Z)^2 + D*\ln(Z)^3 + \ldots + G*\ln(Z)^6} \tag{8}$$

TABLE I. CONSTANTS USED BY KINGERY & BULMASH IN THEIR STUDY TO DETERMINE THE INCIDENT PRESSURE.

<table>
<tr><th colspan="4">Incident Pressure, P_I (Units: kPa (psi))</th></tr>
<tr><th>Z</th><th colspan="2">K0</th><th>K1</th></tr>
<tr><td rowspan="12">0,05~40
(0,132~100)
Units:
m/kg^1/3
(ft/lb1/3)</td><td colspan="2">-0,214362789151</td><td>1,35034249993</td></tr>
<tr><td colspan="2">(-0,756579301809)</td><td>(1,35034249993)</td></tr>
<tr><th>C0</th><th>C1</th><th>C2</th></tr>
<tr><td>2,661368669</td><td>-1,69012801396</td><td>0,00804973591951</td></tr>
<tr><td>(1,77284970457)</td><td>(-1,69012801396)</td><td>(0,00804973591951)</td></tr>
<tr><th>C3</th><th>C4</th><th>C5</th></tr>
<tr><td>0,336743114941</td><td>-0,00516226351334</td><td>-0,0809228619888</td></tr>
<tr><td>(0,336743114941)</td><td>(-0,00516226351334)</td><td>(-0,0809228619888)</td></tr>
<tr><th>C6</th><th>C7</th><th>C8</th></tr>
<tr><td>-0,00478507266747</td><td>0,00793030472242</td><td>0,0007684469735</td></tr>
<tr><td>(-0,00478507266747)</td><td>(0,00793030472242)</td><td>(0,0007684469735)</td></tr>
</table>

Reference: Kingery and Bulmash [6]

TABLE II. CONSTANTS USED BY SWISDAK IN HIS STUDY TO DETERMINATE THE INCIDENT PRESSURE.

Incident Pressure, P_I (Units: kPa (psi))							
Z	**A**	**B**	**C**	**D**	**E**	**F**	**G**
0,2~2,9	7,2106	-2,1069	-0,3229	0,1117	0,0685	0	0
(0,5~7.25)	(6,9137)	(-1,4398)	(-0,2815)	(-0,1416)	(0,0685)	(0)	(0)
2,9~23.8	7,5938	-3,0523	0,40977	0,0261	-0,01267	0	0
(7,25~60)	(8,8035)	(-3,7001)	(0,2709)	(0,0733)	(-0,01267)	(0)	(0)
23,8~198.5	6,0536	-1,4066	0	0	0	0	0
(60~500)	(5,4233)	(-1,4066)	(0)	(0)	(0)	(0)	(0)

Reference: Swisdak Jr [7]

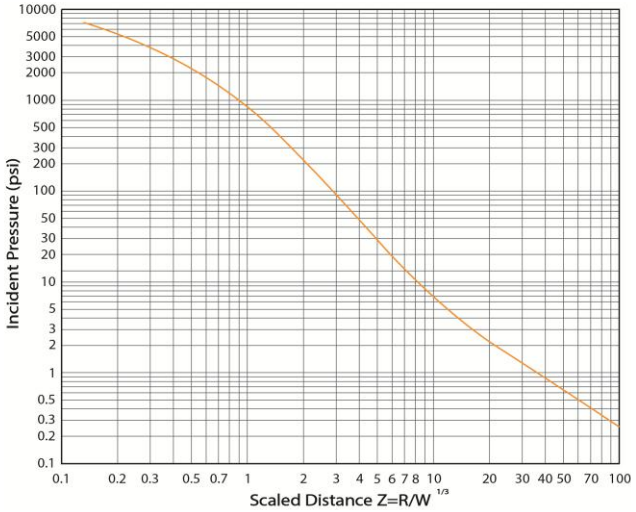

Figure 2. Incident Pressure for a hemispherical TNT explosion on the Surface al Sea Level.
Reference: US Department of Defense [2]

Similarly, the UFC manual [2] through Fig. 2 allows to determine the incidence pressure of a shock wave for a Spherical charge of TNT outdoors and at sea level. All the aforementioned methods were used to determine and compare P_I values.

III. ANALYSIS AND DISCUSSION OF RESULTS

Table III presents the P_I values for a spherical charge of 1 kg of TNT outdoors. These results show that in a range of 0 to 30 m distance the maximum P_I values were obtained by Swisdak Jr [7], while from 50 m distance the Sadovsky [9] model presents values higher than the rest of the models.

Tables IV and V present the results of P_I for a spherical charge of 3 kg and 5 kg of TNT outdoors, respectively, which reflect that the Swisdak model obtains the maximum incidence pressure values for a range of 0 to 50 m away; nevertheless, after 100 m the Sadovsky model is the superior of all the analyzed ones.

TABLE III. INCIDENT PRESSURE FOR A SPHERICAL CHARGE OF 1KG OF TNT.

Distance	**Z**	**(Henrych, 1979)**	**(Sadovsky, 2004)**	**(Kingery & Bulmash, 1984)**	**(Swisdak, 1994)**	**(UFC, 2008)**
m	m/kg$^{1/3}$	KPa	kPa	kPa	kPa	kPa
15	15	-	7,2370	7,3156	8,7584	5,8045
30	30	-	3,1963	2,8426	3,5590	2,5623
50	50	-	1,8264	-	1,7349	-
100	100	-	0,8808	-	0,6544	-
300	300	-	0,2867	-	-	-

TABLE IV. INCIDENCE PRESSURE FOR A SPHERICAL CHARGE OF 3KG OF TNT.

Distance	**Z**	**(Henrych, 1979)**	**(Sadovsky, 2004)**	**(Kingery & Bulmash, 1984)**	**(Swisdak, 1994)**	**(UFC, 2008)**
m	m/kg$^{1/3}$	kPa	kPa	kPa	kPa	kPa
15	10,40	-	11,6573	11,8090	14,1144	9,838
30	20,80	-	4,8686	4,7348	5,8078	3,809
50	34,67	-	2,7206	2,3270	2,9039	-
100	69,34	-	1,2907	-	1,0953	-
300	208,01	-	0,4157	-	-	-

TABLE V. INCIDENCE PRESSURE FOR A SPHERICAL CHARGE OF 5KG OF TNT.

Distance	**Z**	**(Henrych, 1979)**	**(Sadovsky, 2004)**	**(Kingery & Bulmash, 1984)**	**(Swisdak, 1994)**	**(UFC, 2008)**
m	m/kg$^{1/3}$	kPa	kPa	kPa	kPa	kPa
15	8,77	13,2881	14,7737	14,8720	17,8749	12,7556
30	17,54	-	5,9678	5,9534	7,1918	4,7107
50	29,24	-	3,2898	2,9468	3,6898	2,6267
100	58,48	-	1,5452	-	1,3918	-
300	175,44	-	0,4944	-	0,2968	-

The P_I selection process for each condition (that is, 1 kg, 3 kg and 5 kg) was carried out in reference to the maximum values of all the models analyzed.

Fig. 3 shows the correlation of the P_I results with the ranges established by Zipf and Cashdollar [10] for the effect of infrastructure damage; as can be seen for a mass of 1, 3 and 5 kg of TNT, considerable damage occurs at a distance of less than 20, 28 and 30 m measured from the detonation point, respectively. In addition, in the case of 5 kg of TNT, damage at distances less than 20 m from the detonation point will be catastrophic. For all the cases studied there is a low probability (<10%) of damage from 100 m away, being considered as a safe area for infrastructure and equipment. It is important to emphasize that the damage produced in residential structures and homes can cause injuries or death of people according to the magnitude of the case.

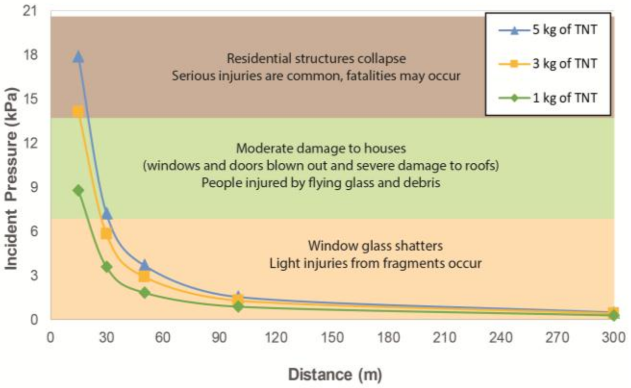

Figure 3. Damage effect for infrastructure and people for 5 kg of TNT.

Based on the estimated damage parameters and the different ranges of critical pressures established by Kinney and Graham [12], the present study determines the estimated distance at which said parameters are reached for spherical charges of up to 5 kg of TNT (see Table VI).

TABLE VI. DAMAGE EFFECT FOR INFRASTRUCTURE AND PEOPLE FOR 5 KG OF TNT.

Pressure (kPa)	Distance (m)	Damage
1.0 – 1.5	> 100	Window glass shatters
3.5 – 7.6	100 – 30	Less damage to some structures
7.6 – 12.4	30 – 15	Deformation in metal panels
12.4 – 20	< 15	Damage to concrete walls

Reference: Kinney and Graham [12]

The study by White, Jones [11] shows the survival rate for an average 70 kg person who is subject to the impact of pressure by a shock wave generated by the detonation of an explosive, Fig. 4 correlates these survival rates with the maximum incidence pressure. These data are compared with the incidence pressure curve determined for the critical charge (5kg of TNT). Achieving at its intersection the maximum value of P_I that an average person can withstand, from which said pressure would become lethal. Subsequently, this result is derived in the determination of the minimum distance (7 m) to which a person must be located at the time of detonation, in order not to suffer lethal damage. It should be noted that although at this distance there is no risk of fatality, injuries are considered severe.

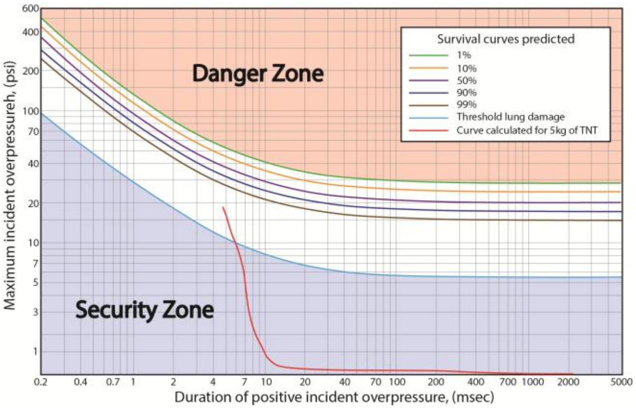

Figure 4. Survival curves predicted for a person.
Reference: White, Jones [11]

Based on the data previously analyzed, Fig. 5 presents the geographical delimitation of each of the security zones, where (i) the red one (radius = 7 m) presents total destruction of equipment, infrastructure and zero probability of survival of the personal, (ii) the orange one (radius = 20 m) allows the remote operation of the filming equipment with minimal damage caused by the explosive wave, however safety measures must be taken in the face of the fragmentation effect of any object subject to the shock wave, (iii) the yellow one (radius = 30 m) is a safe area for the filming equipment and personnel with the appropriate specialized protection [fragment shields, helmets and vests for explosives] and (iv) the green one (radius = 300 m) represents the safe area for filming equipment and personnel without the need to use any type of protection.

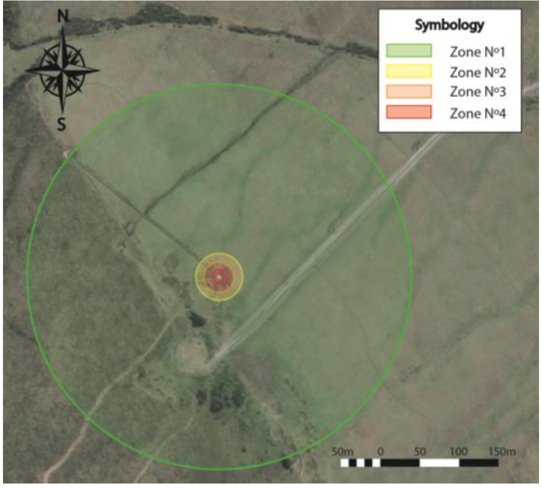

Figure 5. Delimitation of safety zone.

IV. CONCLUSION

Finally, this investigation determines safety zones to carry out work with explosives, correlating the maximum incidence pressure (17.8749 kPa) with the effects of damage to infrastructure and survival rates for people, in this way it is defined that the optimum filming location (a 30 m from the detonation point) and the safe zone of protection (range of 30 m to 300 m) established in a specific geography and topography, free of obstacles or in the open field.

The results of P_I presented in Table III, show that Swisdak's empirical method presented the most conservative values for 1 kg of TNT in the range of 0 to 30 m; from which, Sadovsky is the most conservative method. In the case of 3 and 5 kg of TNT (see Table IV and 5 respectively), it was shown that Swisdak is the most conservative method in a range of 0 to 50 m, after that range, Sadovsky presents the most conservative P_I values. From which, it is established that the critical charge (5 kg of TNT), presents the greatest danger of fatality in people at a distance of less than 7m and a low probability of affecting people over distances greater than 100m from the point detonation

Based on what has been analyzed above, safe areas are established with the construction of two 3 m high berms. The first must be located at the detonation point (0 m) for the protection of the access road to the detonation polygon and the second must be located in the staff meeting area (300 m) in order to counteract the wave of shock that is associated with the incidence pressure, amount of explosive and affectation distance.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Nestor Mejía conducted the research and revised the paper; Angel Sarango and Ricardo Peralra analyzed the data and wrote the paper; all authors had approved the final version.

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