EVALUATING HUMAN TOLERANCE UNDER THE EFFECT OF SHOCK WAVE PRESSURE FROM SURFACE EXPLOSIONS

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Abstract

Protecting individuals and structures from the effects of blast loading is a critical challenge when calculating and designing defensive structures. Shock waves, fragments, and the acceleration of structures caused by explosions will cause lethal damage to humans, equipment, and structures. To ensure safety, studies and standards in Vietnam for calculating safe distances for construction and humans in mining operations and defence structure constructions have been implemented. However, detailed studies on the impact of blast wave pressure on humans, depending on the position, the posture of the victims, the direction of the blast loading, and varying degrees of impact due to weight, have not been specifically researched. Hence, this article will introduce and use UFC 3-340-02, "Structures to resist the effects of accidental explosions", to develop a procedure for assessing the safe distances for humans affected by the pressure of ground blast loading. The result can be applied to automatically estimate the survival probability of humans under the impact of blast loading on the ground.

Keywords: *Blast explosion; shock wave; human tolerance; UFC 3-340-02.*

1. Introduction

Predicting human tolerance under the impact of blast waves from terrorist attacks as well as gas explosions is a challenging problem that has been addressed and is still being developed in Vietnam and the world. When an explosion occurs, explosive products, including shock waves, debris, fragments, and rapid acceleration of the structure, will dangerously impact humans and buildings [1], [2]. Estimating the safe distance and evaluating the probability of damage to humans and structures is also essential. Therefore, the ability to accurately estimate safe distances and evaluate the probability of damage is an essential and ongoing concern for engineers and safety planners in Vietnam and around the world.

In Vietnam, standards such as QCVN 01:2019/BCT [3] have been implemented to calculate safety distances for mining and defense constructions. However, detailed research concerning the specific impact of blast wave pressure on humans - considering variables such as a victim's posture, orientation to the blast, and body weight - has not been fully developed.

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To address this research gap, this article focuses on the factors that directly affect human vitality, specifically the impact of shock wave pressure from a ground explosion. While other factors like thermal effects and fragments are critical components of a blast event, they are beyond the scope of this particular study and will be addressed in future work. To address this, the article introduces the method and procedure for calculating blast loading based on UFC 3-340-02 [4], [5]. By using the framework of predicting human injuries experiment developed in the standard, this study will assess safe distances and predict the levels of human tolerance under the pressure of ground blast loading.

2. Explosions

2.1. Explosion definition

A blasting explosion is a large-scale, sudden, fast energy release from a chemical reaction. After detonating, a condensed high explosive creates hot gases with high pressure and temperature. The hot gas expands, forcing out the volume it occupies. As a result, a layer of compressed air (blast wave) forms in front of this gas volume, containing most of the energy released by the explosion. Blast waves instantaneously increase the pressure value above the ambient atmospheric pressure. Overpressure decays as the shock wave expands outward from the explosion source. After a short time, the pressure behind the front may drop below the ambient pressure (Fig. 1). During such a negative phase, a partial vacuum is created, and the air is sucked in. The phenomenon is also accompanied by high suction winds that carry the debris long distances from the explosion source.

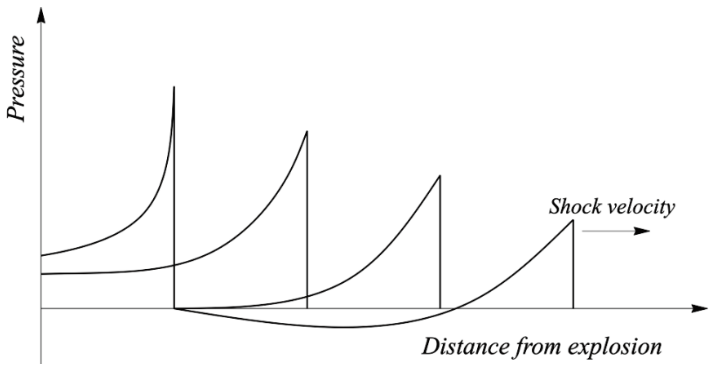


Fig. 1. Variation of blast pressure with distance.

2.2. Blast loading categories

Blast loads can be categorized according to the confinement of the environment around the explosive device. Table 1 clearly distinguishes blast loading categories based on charge confinement, proximity to the ground surface, and 'venting' characteristics.

Tab. 1. Blast loading categories [4]

Charge confinement	**Category**	**Pressure loads**
Unconfined (external) explosions	1. Free-air explosion	Unreflected shock
	2. Air explosion	Reflected shock
	3. Surface explosion	Reflected shock
Confined (internal) explosions	4. Fully vented	Internal shock
		Leakage
	5. Partially confined	Internal shock
		Internal gas
		Leakage
	6. Fully confined	Internal shock
		Internal gas

2.3. Calculating blast loading of the surface explosion

If the centre of charge is close to the ground, the explosion is called a surface explosion. The initial blast wave is reflected and amplified by the reflection of the ground. Unlike an explosion in the air, the refracted wave is combined with the initial wave at the detonation point, forming a single wave (Fig. 2).

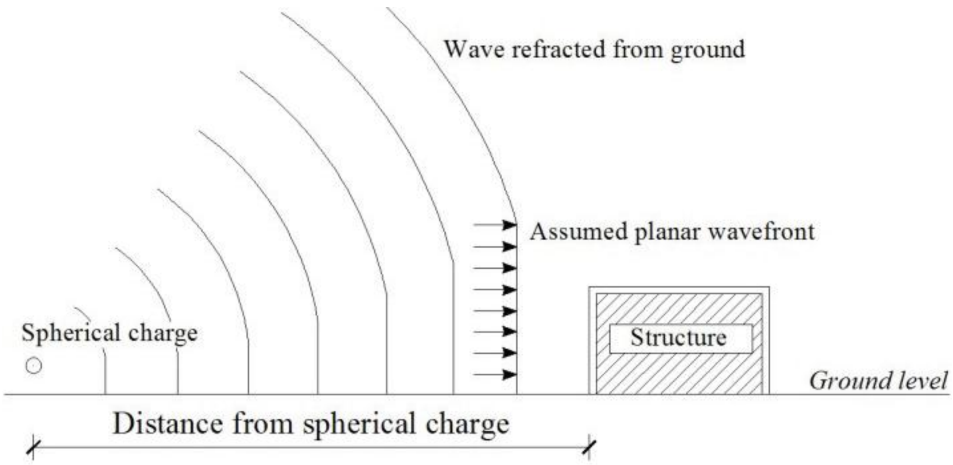


Fig. 2. Surface explosion.

2.4. Determine parameters of blast loading on the ground

There are several empirical methods used to estimate blast loading parameters on the ground (near ground). Newmark and Hansen introduced a function that is widely used for computing peak overpressure values for ground surface blasts [1], [6]:

$$P_{so} = 6784 \cdot \frac{W}{R^3} + 93 \cdot \left(\frac{W}{R}\right)^{\frac{1}{2}} (\text{bars})$$

where P_{so} is the peak pressure at the calculating point in *bars*, Z_G is the scaled ground distance ($Z_G = R/W^{1/3}$), R is the distance between the centre of charge and the target in *m*, W is the equivalent weight of TNT in *Ton*.

Another expression of the peak overpressure in kPa is introduced by Mills [7], in which W is expressed in kg of TNT and the scaled distance Z is in m/kg$^{1/3}$:

$$P_{so} = \frac{1172}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} (\text{kPa})$$

The most widely used and accepted formulation for the determination of blast parameters for both spherical (free air bursts) and hemispherical pressure waves (surface bursts) is one proposed by Kingery-Bulmash [8]. Their research provides the values of incident and reflected pressures as well as of all other parameters.

Although using the analytical formula is simple and increases safety, the function is limited by ignoring the loss of energy due to the interaction between the blast and the ground. Moreover, the function also overlooks the effect of the explosion height and disregards the effect of the angle of the incident wave. On the contrary, the UFC 3-340-02 standard uses experimental data to get the parameters of blast loading [4], [6]-[10].

The procedure has been introduced to determine free-field blast wave parameters for a surface burst by following step by step [4]:

Step 1. Select a point of interest on the ground relative to the charge. Determine the charge weight and ground distance R_G.

Step 2. Apply a 20% safety factor to the charge weight.

Step 3. Calculate scaled ground distance Z_G

Step 4. Determine free-field blast wave parameters from Fig. 3 for corresponding scaled ground distance Z_G:

After using plot software, the data can be read and extracted to get information:

Peak positive incident pressure P_{so}

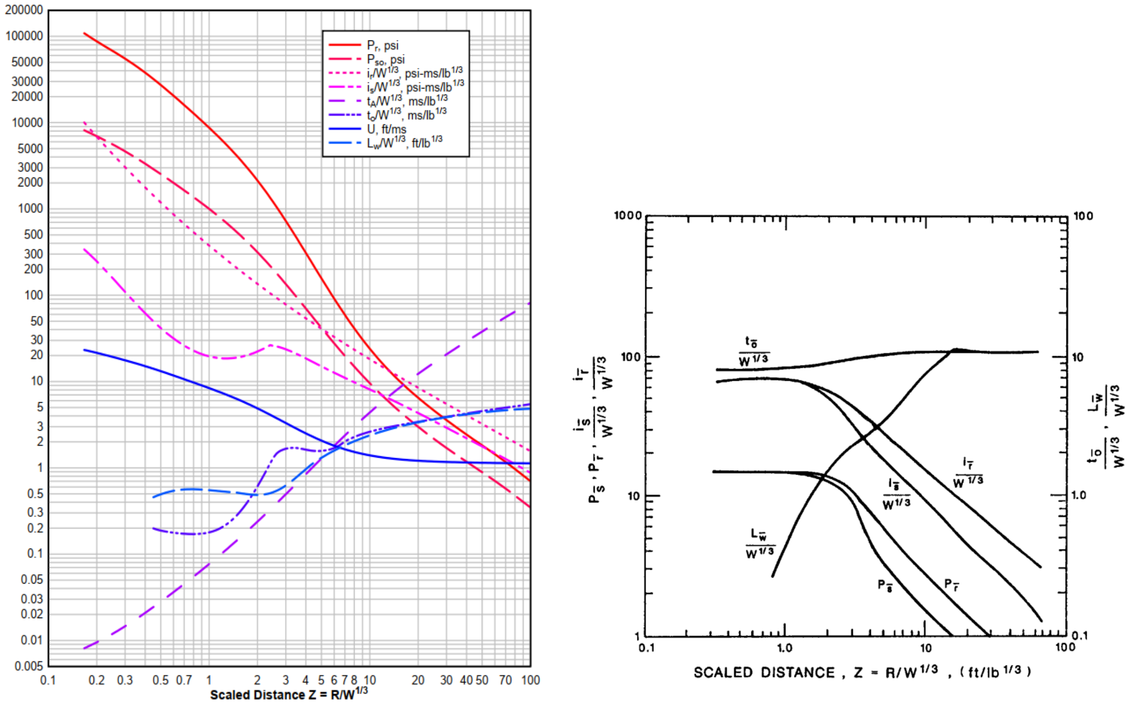
Shock front velocity U

Scaled unit positive incident impulse $i_s/W^{1/3}$

Scaled positive phrase duration $t_o/W^{1/3}$

Scaled arrival time $t_A/W^{1/3}$

Multiply scaled values by $W^{1/3}$ to obtain absolute values. The database has been integrated and shown in Fig. 3 in digital format (Dplot files).



a) Positive phase shock wave parameters for a hemispherical TNT explosion on the surface at sea level

b) Negative phase shock wave parameters for a hemispherical TNT explosion on the surface at sea level

Fig. 3. Figures to calculate the shockwave parameters for hemispherical TNT explosion on the surface [4].

3. Human tolerance

The modelling of injury and explosion effects considered below concerns mainly events in open spaces. Traditionally, four basic mechanisms of blast injury are distinguished: primary, secondary, and tertiary. They are demonstrated in Fig. 4.

To calculate blast-safe distances, the Vietnamese standard QCVN 01:2019/BCT [3] has detailed calculation method guidelines for determining the safety distances of constructions under the effect of blast loading. All influencing factors have been taken into account when calculating the safety ranges, which can be fully used to estimate human safety distance, although the results tend to lean towards safety.

Meanwhile, UFC 340-3-02 can estimate in detail the impact of each factor based on experimental data, such as the impact of the blast wave's overpressure, the impact and range of impact of fragments caused by explosions, and other tertiary factors.

In the scope of the study, the article focuses solely on examining the impact of pressure, disregarding other factors.

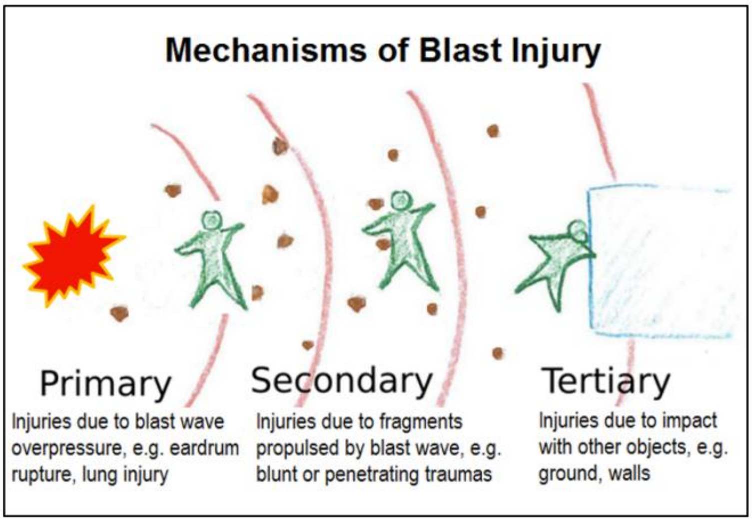


Fig. 4. Schematic representation of blast injury mechanisms [12].

3.1. Blast injuries

Research on the effect of blasts on the survival ability of humans has been conducted for a long time. The standard UFC 3-340-02 also illustrates that human tolerance to blast energy from an explosion is relatively high. However, depending on the position of a person (standing, sitting, prone, face-on or side-on to the pressure front) relative to the blast front, as well as the characteristic of the pressure front (rapid or slow ascent, stepped loading), the amount of endured injury will be determined. Shock tube and explosive examinations have shown that human blast tolerance varies with both the magnitude and duration of the shock, i.e., pressure tolerance for short-duration blast loads is much greater than that for long-duration blast loads [4], [5], [9].

Studies have found that the lungs are the primary target of blast injuries, with the impact of blast waves on the air-filled tissues of the lungs causing significant damage. In the case of short blast duration (3 to 5 ms), Tab. 2 shows that severe lung haemorrhage can occur at peak pressures between 40-80 psi, while death from lung injury is likely above 100-120 psi. On the other hand, the threshold pressure level for petechial haemorrhage resulting from long-duration loads may be as low as 10 to 15 psi, or approximately one-third that for short-duration blast loads (Fig. 5). Because human survival under the effect of blasting depends on the human's mass, it is recommended that survival calculating should be applied with 11 lb for babies, 55 lb for small children, 121 lb for adult women and 154 lb for adult males.

Tab. 2. Blast effects in man applicable to fast-rising air blasts of short duration (3-5 ms)

Critical Organ or Event	Maximum Effective Pressure (psi)*
Eardrum Rupture	
Threshold	5
50 percent	15
Lung Damage	
Threshold	30-40
50 percent	80 and above
Lethality	
Threshold	100-120
50 percent	130-180
Near 100 percent	200-250

* Maximum effective pressure is the highest of incident pressure, incident pressure plus dynamic pressure, or reflected pressure.

Beside the damage to the lungs, the blast wave also impacts the eardrums. Fig. 6 shows the direct relationship between the percentage of ruptured eardrums and maximum pressure. This figure shows that at a pressure of 15 psi for fast-rising pressures, 50 percent of exposed eardrums rupture, while the threshold of eardrums ruptures for fast-rising pressure is 5 psi. Temporary hearing loss can occur at pressure levels less than the pressure that makes the eardrum rupture. Temporary hearing loss is a function of the pressure and impulse of a blast wave affecting the eardrum. The lowest curve in Fig. 6 represents the case where 90 per cent of people exposed suffered temporary hearing loss or temporary threshold shift. The pressures referred to above are the maximum effective pressures, the highest of the incident pressure, or the reflected pressure.

The maximum effective distance for a human depends on the type of pressure, the orientation of the individual relative to the blast, the reflection of the blast, and the occurrence of opening effects, which will cause pressure amplification when the blast wave passes through openings.

For example, lung injury depends on various positions and locations. The threshold of overpressure would be 30 to 40 psi due to reflected pressure for personnel against a reflector (any position), 30 to 40 psi incident plus dynamic pressure, 20 to 25 psi incident pressure plus 10 to 15 psi dynamic pressure for individual with standing or prone-side-on posture, and 30 to 40 psi incident pressure for personnel in the open in a prone-end-on position.

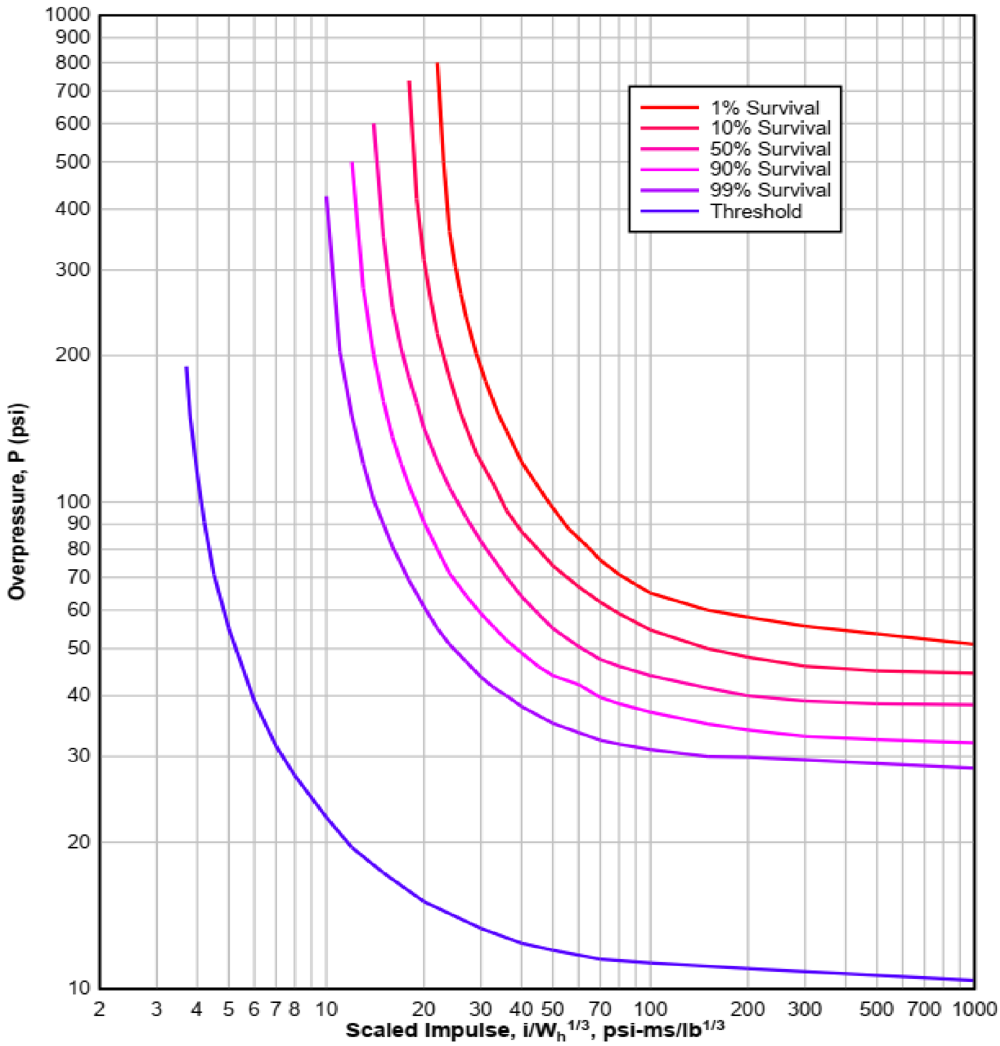


Fig. 5. Survival curves for lung damage, W_h - weight of human being (lbs) [4].

However, the experimental data above also assumes that an individual is supported and will not be injured by falling or impacting with a hard surface. In this case, pressure levels that humans can withstand are generally much lower than those that cause eardrum or lung damage. It is recommended that the tolerable pressure level of humans not exceed 2.3 psi, which is higher than the temporary threshold shift of temporary hearing loss (Fig. 6) and probably will cause personnel in the open to be thrown off balance.

In addition to the impact of blast loading, the impact of fragments on humans must also be calculated. However, because of the complex problem and the article's limit, the article only focuses on the influence of blast loading on human tolerance.

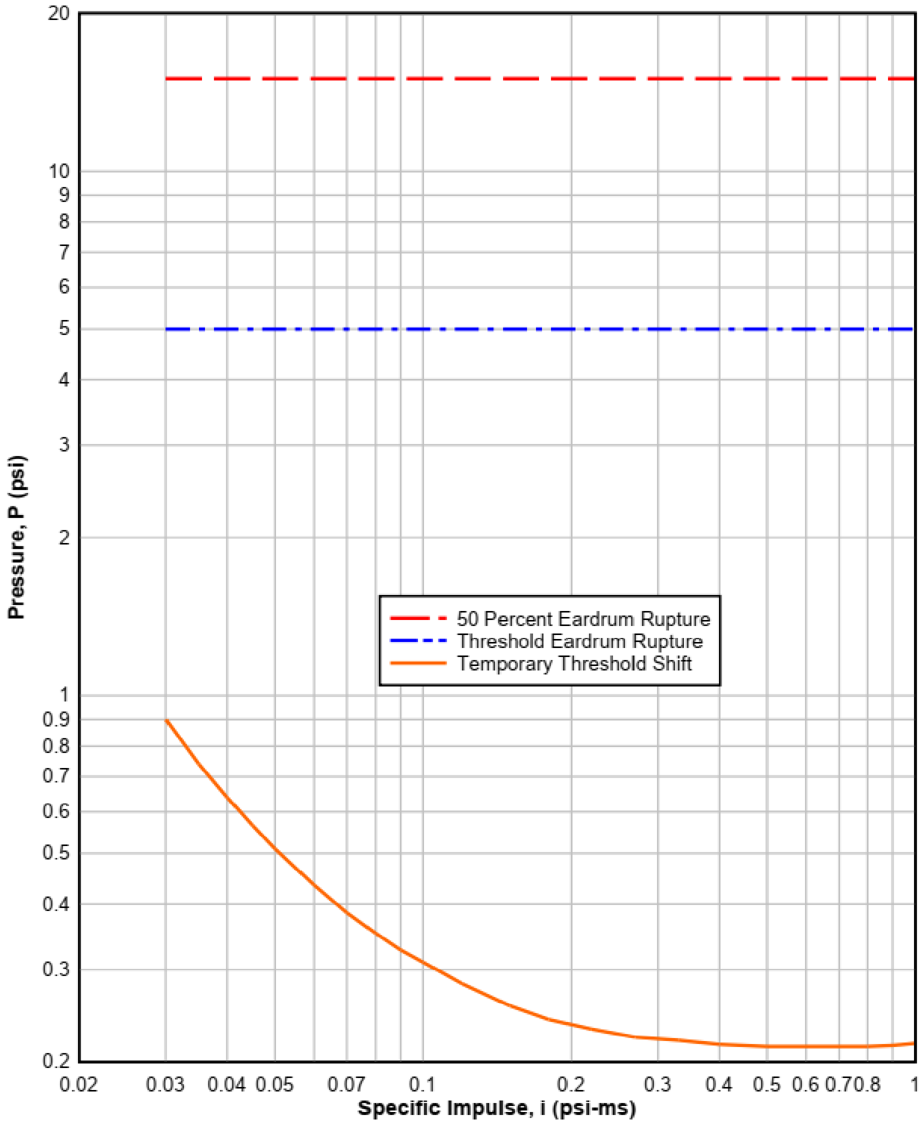


Fig. 6. Human ear damage due to blast pressure [4].

3.2. Estimating the ability of survival of humans under the effect of blast loading of ground explosion

Based on the experimental data of UFC 3-340-02, the digital data has been extracted and transferred into Excel. The function of calculating blast loading has been developed to calculate it. After that, the safety distance for humans has been estimated, assuming that there is no obstacle on the ground and the explosive weighs 250 lbs.

Depending on the distances between the survey points and the explosive, parameters of blast loading have been calculated by using the procedure given in Section 2.3.

Tab. 3. Blast loading results

Distance R (ft)	Distance R (m)	P_r (psi)	P_{so} (psi)	P_{so} (kg/cm^2)	ir (psi-ms)	i_s (psi-ms)	t_a (ms)	U (ft/ms)	t_o (ms)	P_{so} (Shadoxki) (kg/cm^2)
15.00	4.57	1610.39	251.30	17.67	729.14	155.14	1.83	4.40	5.60	22.55
20.00	6.10	736.62	136.24	9.58	495.68	149.59	3.09	3.32	10.45	10.56
25.00	7.62	381.31	82.26	5.78	371.49	124.43	4.68	2.67	10.50	6.00
30.00	9.14	219.25	54.03	3.80	295.42	104.83	6.59	2.27	9.90	3.84
32.50	9.91	171.85	44.90	3.16	267.57	97.15	7.65	2.12	9.88	3.18
35.00	10.67	137.49	37.89	2.67	244.39	90.61	8.78	2.00	10.00	2.67
37.50	11.43	112.02	32.40	2.28	224.81	84.99	9.98	1.90	10.25	2.28
40.00	12.19	92.72	28.03	1.97	208.03	80.10	11.24	1.81	10.65	1.97
50.00	15.24	49.64	17.23	1.21	159.80	65.64	16.79	1.58	13.55	1.22
60.00	18.29	31.09	11.85	0.83	129.42	56.02	23.00	1.45	15.50	0.84
70.00	21.34	21.69	8.79	0.61	108.65	49.01	29.70	1.37	16.88	0.63
80.00	24.38	16.27	6.88	0.48	93.54	43.60	36.75	1.32	17.93	0.49
90.00	27.43	12.88	5.61	0.39	82.11	39.26	44.03	1.29	18.78	0.40
100.00	30.48	10.58	4.70	0.33	73.12	35.69	51.48	1.26	19.51	0.33
110.00	33.53	8.9476	4.03	0.28	65.91	32.69	59.05	1.24	20.16	0.28
120.00	36.58	7.7324	3.52	0.25	59.99	30.14	66.71	1.225	20.75	0.25
150.00	45.72	5.4469	2.53	0.18	47.22	24.38	90.00	1.195	22.31	0.18

Figure 7 also illustrates that the deferences between the peak positive incident pressure calculated by the two methods are the same. The advantage of UFC 3-340-02 is that it can be used to determine the reflected maximum pressure, impulse, arrival time, and positive duration.

Using the calculated data above and using them to compare with survival, ear damage, lung damage and lethality conditions, the threshold distance will be shown:

1) The safe distance is 150 ft (45.7 m). Everyone standing out the distance will be safe under only the effect of blast wave.

2) The threshold distance which will cause the onset of lung injury to personnel in various positions and locations:

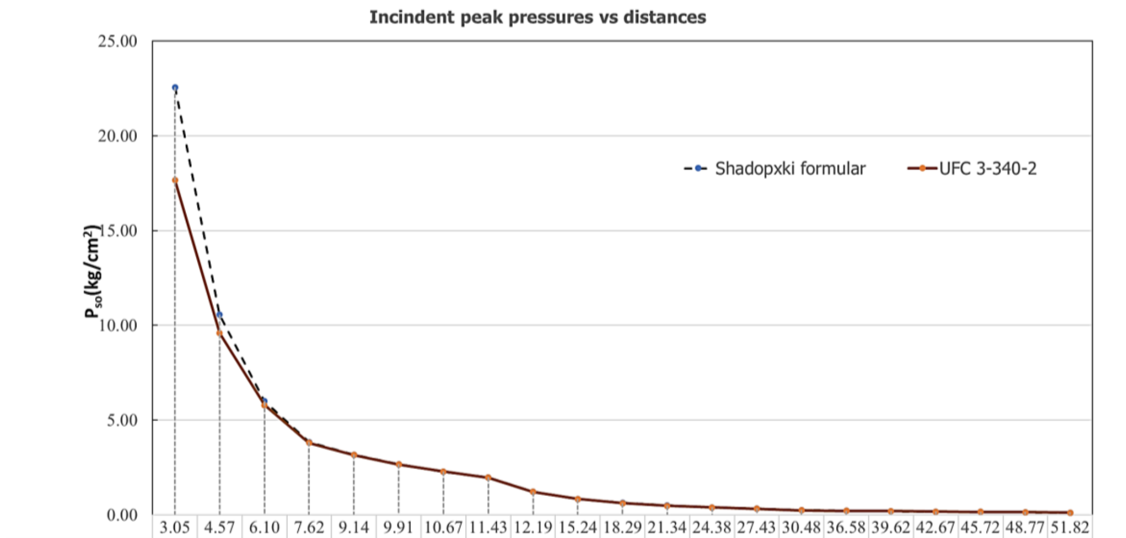
- Personnel in the open in a prone-end-on position: 18 m;
- Personnel in the open: approximately 21 m;
- Personnel against a reflector like buildings, cars (any position): 13 m;

3) The threshold distance which will cause temporary hearing loss: 29.5 m;

4) The threshold distance which will cause 50% ruptured eardrums: 16.5 m;

5) The threshold distance which will cause lethality: 7.1 m;

6) The threshold distance which will cause 100% lethality 5.2 m.



	3.05	4.57	6.10	7.62	9.14	9.91	10.67	11.43	12.19	15.24	18.29
Shadopxki formular	22.55	10.56	6.00	3.84	3.18	2.67	2.28	1.97	1.22	0.84	0.63
UFC 3-340-2	17.67	9.58	5.78	3.80	3.16	2.66	2.28	1.97	1.21	0.83	0.62

	21.34	24.38	27.43	30.48	36.58	39.62	42.67	45.72	48.77	51.82
Shadopxki formular	0.49	0.40	0.33	0.25	0.22	0.20	0.18	0.16	0.15	0.12
UFC 3-340-2	0.48	0.39	0.33	0.25	0.22	0.20	0.18	0.16	0.15	0.12

distance (m)

Fig. 7. Comparisons peak positive incident pressure calculated by Shadoxpki vs UFC 3-340-02.

4. Conclusion

The article has presented a new method and procedure for calculating human tolerance under the effect of shock wave pressure of a surface explosion. Based on the reflected or incident pressures and the conditions of human tolerance, the threshold distances can be calculated and illustrated to predict and help the government find a solution to reduce human damage. In the article, the safe distance and the threshold distance has been calculated for human under the effect of blast loading of the explosive weighs 250 lbs denonated on the ground. The result shown that a person would be safe if the distance between they and the center of explosive more than 21 m. Furthermore, the developing calculation method can be also completely applied and deployed to calculate and compare the effects of explosions and various explosive loads on human tolerance and damage levels.

However, in order to calculate the probability of human tolerance in more detail, it is necessary to build damage distribution functions and P-I relationships (pressure and impulse). This important problem, as well as the secondary effects of explosions on human tolerance, will have been studied in the near future.

References

[1] T. D. Ngo *et al.*, "Blast loading and blast effects on structures – An overview", *Electronic Journal of Structural Engineering*, Vol. 7, No. 1, pp. 76-91, 2007. DOI:10.56748/ejse.671

[2] Š. Ji and D. Petr, “Structural damage diagnostics on cement composites after blast load”, *2017 International Conference on Military Technologies (ICMT)*, pp. 211-216, 2017. DOI: 10.1109/MILTECHS.2017.7988758

[3] *Quy chuẩn kỹ thuật quốc gia về an toàn trong sản xuất, thử nghiệm, nghiệm thu, bảo quản, vận chuyển, sử dụng, tiêu hủy vật liệu nổ công nghiệp và bảo quản tiền chất thuốc nổ*, QCVN 01:2019/BCT, Hà Nội, 2019.

[4] U.S. Army Corps of Engineers, “UFC 3-340-02 Unified Facilities Criteria (UFC) structures to resist the effects of accidental explosions”, 2014. [Online]. Available at: http://dod.wbdg.org/

[5] P. F. Acosta, “Overview of UFC 3-340-02 structures to resist the effects of accidental explosions”, in *Structures Congress 2011*, Reston, VA: American Society of Civil Engineers, Apr. 2011, pp. 1454-1469. DOI: 10.1061/41171(401)127

[6] N. M. Newmark and R. J. Hansen, “Design of blast resistant structures”, in *Shock and Vibration Handbook*, Vol. 3, McGraw-Hill, 1961.

[7] C. Mills, “The design of concrete structures to resist explosions and weapon effects”, in *Proceedings of the 1st International Conference on Concrete for Hazard Protections*, Edinburgh, UK, 27-30 September 1987, pp. 61-73.

[8] C. N. Kingery and G. Bulmash , “Technical report ARBRL-TR-02555: Air blast parameters from TNT spherical air burst and hemispherical burst”, 1984.

[9] M. A. Polcyn and K. D. Myers, *Use of SBEDS for Blast Resistant Design in Accordance with UFC 3-340-02*. Defense Technical Information Center, 2010. [Online]. Available at: https://books.google.com.vn/books?id=gRxRAQAACAAJ

[10] A. Darabi *et al.*, “Cognitive presence in asynchronous online learning: A comparison of four discussion strategies”, *Journal of Computer Assisted Learning*, Vol. 27, No. 3, pp. 216-227, June 2011. DOI: 10.1111/j.1365-2729.2010.00392.x

[11] H. Draganić and V. Sigmund, “Blast loading on structures”, *Technical Gazette*, Vol. 19, No. 3, pp. 643-652, 2012.

[12] S. George *et al.*, “A survey of computational models for blast induced human injuries for security and defence applications”, 2020. DOI: 10.2760/685

ĐÁNH GIÁ NGƯỠNG CHỊU ĐỰNG CỦA CON NGƯỜI DƯỚI TÁC DỤNG CỦA ÁP LỰC SÓNG XUNG KÍCH TỪ VỤ NỔ TRÊN MẶT ĐẤT

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Tóm tắt: Bảo vệ con người và công trình khỏi tác động của tải trọng nổ là một thách thức quan trọng khi tính toán và thiết kế các công trình phòng thủ. Sóng xung kích, mảnh vỡ và gia tốc của các công trình do vụ nổ gây ra có thể gây ra các thiệt hại nguy hiểm cho con người, thiết bị và công trình. Để đảm bảo an toàn, các nghiên cứu và tiêu chuẩn tại Việt Nam về tính toán khoảng cách an toàn cho công trình và con người trong hoạt động khai thác mỏ và công trình quốc phòng đã được triển khai. Tuy nhiên, các nghiên cứu chi tiết về tác động của áp lực sóng nổ lên con người, tùy thuộc vào vị trí, tư thế của nạn nhân, hướng tải trọng nổ và các mức độ tác động khác nhau do trọng lượng người, vẫn chưa được nghiên cứu cụ thể. Do đó, bài báo sẽ giới thiệu và sử dụng tiêu chuẩn UFC 3-340-02, "Các công trình chống lại tác động của vụ nổ", để phát triển quy trình phục vụ đánh giá khoảng cách an toàn của con người khi chịu ảnh hưởng của áp lực tải trọng nổ trên mặt đất. Kết quả nghiên cứu có thể được áp dụng để tự động tính toán khả năng sinh tồn của con người dưới tác dụng của vụ nổ trên mặt đất.

Từ khóa: *Tải trọng nổ; sóng xung kích; ngưỡng chịu đựng của con người; UFC 3-340-02.*

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