

ANALYTICAL TOOL FOR MODELING THE DISPERSION OF MATERIAL FRAGMENTS GENERATED BY EXPLOSIVES BLASTING

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Abstract: *The unprecedented increase, in the last decades, of risks, hazards and threats to the vital objectives of states and international bodies, simultaneously with the increase in their number and vulnerability, led to the sedimentation and establishment of the new concept generically called critical infrastructure. The sites where explosives are manufactured, stored and used can be considered as critical infrastructures, especially taking into account the criterion of the extent, the amplitude of the effects of an explosion produced but also the possible severity on the economic activity, the public and the environment. From this perspective, this article presents an analytical tool for modeling the dispersion of material fragments generated by the detonation of explosives based on the quantification of the impact of the throwing speed and the mass of the material fragments, taking into account the type of material and the loading conditions of the resulting debris. The developed tool resorts to the use of a statistical function, namely the probability density function for modeling different types of fragments resulting from explosion-type events.*

Keywords: *explosives, blasting, fragment dispersion, debris, probability density, kinetic energy*

1. Introduction

Research efforts in the field of explosion risk protection, especially for strategic buildings and infrastructures, are not new in the last decades, with several studies being carried out by various research teams with the support of field experiments and/or numerical methods, studies based on different approaches [1, 2, 3].

The approach based on the study of blast-resistant structures is of interest for various types of engineering applications. Several researches have been carried out especially on the structural design and mechanical analysis [4] of blast-resistant and protective structures that could properly withstand blast waves [5].

In general, mitigation measures that can be adopted for explosion protection can be categorized as "non-structural" as well as "structural". In the first case, "non-structural" mitigation measures can be either passive or active. Their purpose is to address the reduction of the probability of occurrence of a certain accidental scenario and thus to minimize the intensity of a possible hazardous event that may occur. An overview of blast mitigation measures for coastal structures was presented in the paper "Characterization of accidental scenarios for offshore structures". Thus, in this work, reference is made to different types of explosion-resistant protective walls. It has been shown that, for example, blast-resistant walls are usually made of steel and/or reinforced concrete, or can be made of prefabricated slabs. Furthermore, explosion-proof walls isolate non-hazardous areas and therefore minimize the effects of explosive charges [6].

The explosion severity approach to the consequence gravity of an explosion is represented by the so-called "Targets", which in this context represent the targets vulnerable to potential explosive events and indicate places that can be selected by terrorist attacks in their effort to maximize the effects, [7] including here the effects of the mass media [8]. These may include critical infrastructure, key resources or key assets that are typically without adequate protection and are open to the public by their purpose. However, explosion scenarios are well known to represent unexpected events that can lead to catastrophic consequences [9].

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The approach based on numerical models: in the paper „*Numerical Analysis of the BlastWave Propagation due to Various Explosive Charges*“, Figuli et al. presents a numerical model for the analysis of the blast wave propagation mode [10]. Based on the research carried out in the last decades, different analytical solutions can be found in the specialized literature [11]. Many other influencing parameters are then involved in the empirical description of an expected blast wave, which is confirmed and may further interact with the soil or affected surfaces [12].

Also in the same approach, in the paper "Characterizing Explosive Effects on Underground Structures", A. H. Chowdhury, T. E. Wilt, present numerical analyzes to characterize the effects that explosions close to the ground surface and in contact with the ground surface have on underground structures, with emphasis on tampered improvised explosive devices [13].

Empirical and experimental information are aided by various numerical analysis techniques with appropriate assumptions, idealizations and simplifications that have been implemented in various restricted-use codes (e.g. defense-related and commercially available computer codes such as ABAQUS and LS-DYNA). Bangash, (2001) considers that attempting to quantify or predict damage modes by analytical methods is extremely difficult [14] and McVay (1988) carried out theoretical and experimental studies on the damage of concrete structures subjected to air blast from hollow and cased explosive charges. Empirical and experimental data were used to estimate whether local damage would occur. It was found, however, that the damage results from the small-scale tests were difficult to scale up to the actual damage states observed in the large-scale tests. Furthermore, damage predictions based on empirical equations did not always predict well small-scale test observations [15].

2. General aspects regarding explosion risk modeling

Explosive substances, in the sense of the law, mean explosives themselves, simple explosive mixtures and pyrotechnic mixtures, means of initiation, ignition aids, as well as any other substances or mixtures of substances intended to give rise to instantaneous chemical reactions, with release of heat and gases at high temperature [16, 17, 18].

The modeling of the risk of projecting material fragments following the detonation of explosive materials with a harmful effect on the human component and/or on nearby industrial/civilian objectives is based on the quantification of the impact of the throwing speed and the mass of the material fragments, taking into account the type of material (steel or concrete) and loading conditions of the resulting debris. Models developed to generate trajectory calculations for ranges of mass, launch angles, and launch velocity based on Monte-Carlo simulations are sensitive to the predetermined ranges assigned to each trajectory variable, requiring long intervals of time and IT resources as appropriate, and in the end a detailed result is obtained, based only on assumptions.

If results of explosives testing programs, relevant information on accident history involving hazardous substances such as explosives, and data validated through various simulations are available, fast-running risk analysis models can be created specific, without the need to use physical-mathematical tools (trajectories, resistance equations) in real time for each fragment. In this sense, the paper highlights an analytical tool for using a statistical function, namely the probability density function for modeling different types of fragments resulting from explosion-type events.

Following the occurrence of an explosion-type event, thousands of individual fragments characterized by their own mass and velocity parameters can be generated, resulting in individual energy values that can be taken into account in a quantitative risk assessment, by grouping them into ten distinct classes, so: Class 1 represents fragments with the highest kinetic energy and/or mass, and class 10 represents fragments with the lowest kinetic energy and/or mass. This class system was first developed for the kinetic energy ranges, and the average size masses for steel and concrete fragments were calculated for each class taking into account terminal velocity. Each class has a range of about half an order of magnitude expressed in terms of kinetic energy, the same approximation being valid for the mass parameter.

Table 1 represents the ten distinct classes of the kinetic energy parameter, with the maximum, mean, and minimum values for each class, as well as the average mass for each detached fragment (depending on material type) associated with the energy classes.

Table 1. The distinct classes of the kinetic energy parameter corresponding to each material fragment associated with the energy classes

	Energy class									
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10
Kinetic energy Minimal	100k	30k	10k	3k	1k	300	100	30	10	3
Kinetic energy Average	173k	54k	17k	5k	1,7k	547	173	54	17	5
Kinetic energy Maximal	$\geq 300k$	100k	30k	10k	3k	1k	300	100	30	10
Medium fragments from steel (kg)	16.19	6.75	2.87	1.20	0.51	0.214	0.09	0.038	0.017	0.006
Concrete medium fragments (kg)	34.20	14.28	6.07	2.54	1.07	0.45	0.19	0.08	0.03	0.016

3. Modeling the dispersion of material fragments resulting from the detonation of explosive materials. types of density functions

The modeling of the design effect of debris that can affect the human component and/or the resistance structure of installations and buildings located on a site intended for specific operations with explosive materials is based on the quantification of the impact characterized by the throwing speed and the mass of material fragments resulting in following the detonation of explosive substances, taking into account the type of material (steel or concrete) and the loading conditions of the resulting debris.

Models developed to generate trajectory calculations for ranges of mass, launch angles, and launch velocity based on Monte-Carlo simulations are sensitive to the predetermined ranges assigned to each trajectory variable, requiring long intervals of time and IT resources as appropriate, and in the end a detailed result is obtained, based only on assumptions. If results of explosives testing programs, relevant information on the history of accidents involving hazardous substances such as explosives, and data validated by various simulations are available, fast-running models for risk analyzes can be created specific, without the need to use physical-mathematical tools (trajectories, resistance equations) in real time for each formed fragment.

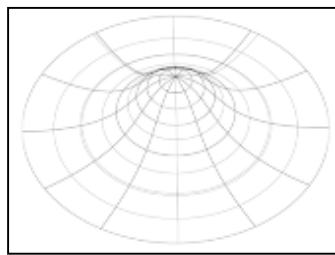
To represent different types of patterns of material fragments resulting from detonation, the probability density functions (fig. 1) can be designed with different levels of complexity, considering the need to faithfully reproduce the patterns of fragments resulting during testing, being described of appropriate mathematical expressions that determine the specific components of variation, respectively:

- *Component 1- $f_{1,2}(r)$* which reproduces the shape of the trajectory from the origin of the explosion outwards in any radial direction (this essential component determines how far from the origin the fragments are thrown as well as the peak density range);
- *Crossed omponent 2 - $f_3(\theta)$* produces the shape of a function when moved radially at a constant interval from the origin (called the cross or azimuth direction).

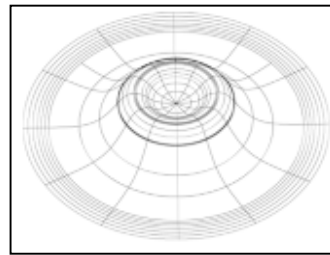
Normal probability distributions (uniform in all directions from the origin i.e. without azimuthal variation) are commonly used to model the design effect uniformly or randomly distributed in all directions around the epicenter of an explosion, such as fragments of material detached from a roof, which are thrown up and scattered, or the debris from the walls of a building structure (Gaussian - Bivariate Normal distribution), according to figure 1. a. The BVN type probability density function is useful for normal scenarios where little data is available, assuming that the larger hazardous debris is close to the explosion epicenter (origin).

However, there are also situations where, following tests with explosives, multiple fragments of material resulting from detonation (primary from explosives and secondary from structural walls) are projected outwards outside the area the epicenter of the explosion. In this case, a BVN-type distribution model used in such scenarios is characterized by a probability density function that tends both to overestimate the level of prediction of fragments located near the epicenter of the explosion (near the origin) and to underestimate the density of fragments within the same class intervals.

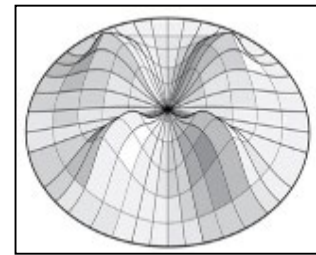
Thus, for modeling the throwing effect, in the case of material fragments that are mostly located outside the area in the vicinity of the explosion epicenter, the total amount of these fragments is kept constant, and the peak of component 1 (which reproduces the shape of the trajectory from the origin of the explosion to outward in any radial direction) of the distribution function is forced outward according to the throw tendency, resulting in a new function component having a toroidal shape (if azimuthal variation is not taken into account), according to Figure 1.b.



a. Gaussian distribution model – Bivariate Normal (BVN)



b. Toroidal distribution model without azimuthal variation



c. Distribution model with nonzero azimuthal variation

Figure 1. Typology of probability distribution models used to model the design effect of fragments of material resulting from the detonation of explosives

The outward forcing of the maximum density range of the projected fragments generates a „volcano” looking variation shape, with the density of fragments in the vicinity of the epicenter being maintained at a non-zero value.

For the most truthful modeling of the design effect of material fragments resulting from the detonation of explosive materials, the new resulting model is used, with non-zero azimuthal variation, according to which the amplitude along the central direction varies according to the class interval of the fragments, and the standard deviation is a constant angle at all these intervals (fig. 1.c).

From a comparative point of view, the two types of curves, respectively BVN and the toroidal type, are characterized by the fact that the areas around them are the same, which means that from a graphical point of view, the same total mass of material fragments resulting from the detonation is represented (fig. 2).

The new function component (fig. 3.a) that generates the toroidal shape model is controlled by three parameters a, b and c that can be modified to represent the variation in the size of the fragments, the type of material of the fragments and their provenance (fragments from structural walls or roof), respectively:

a - is the ratio between the position in the horizontal plane of the peak of the probability curve (X_{max}) and the maximum distance in the same horizontal plane (maximum throw) of the density of the material fragments to be modeled (X_{MT});

b - is the ratio between the probability value of the probability density at the point of origin (Y_0) and the maximum value of the probability density (Y_{max});

c - represents the percentage of the area under the probability curve, delimited between the origin and the peak.

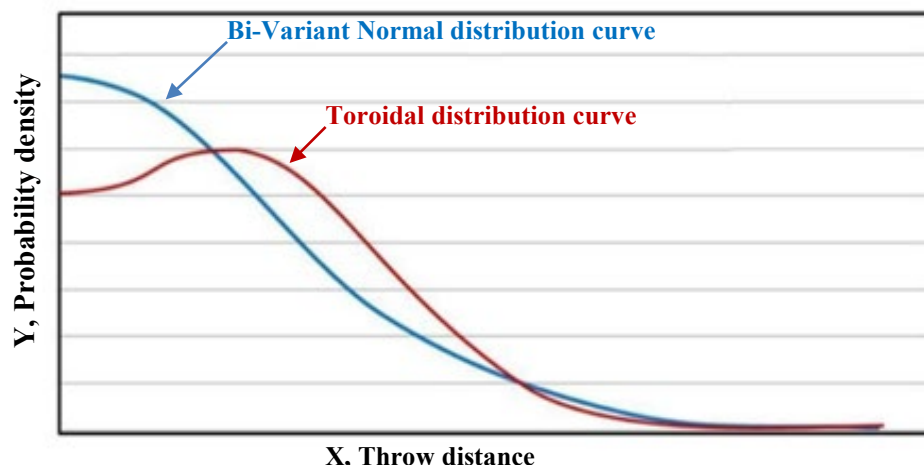
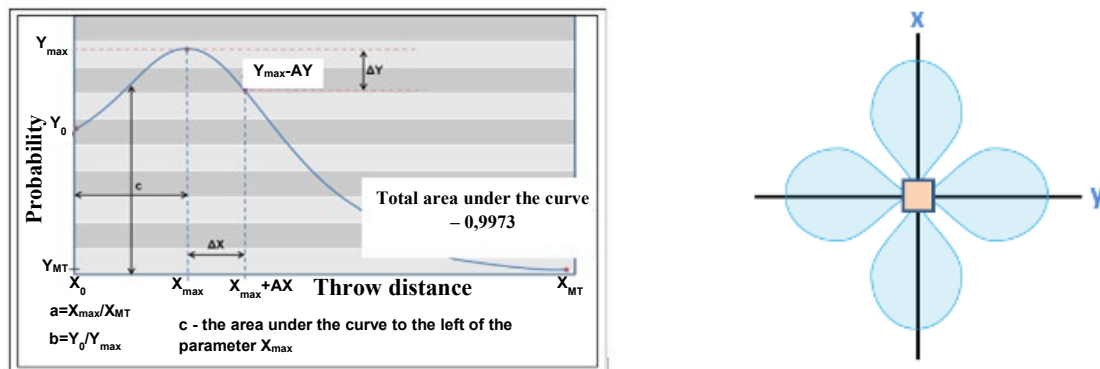


Figure 2. The two types of curves related to the probability distributions used, (BVN and the toroidal type)

In the case of explosive charges located in the central area in parallelepiped buildings, the density of the fragments generated by the detonation is strongly influenced by the azimuth (the fragments coming from the walls of the structure tend to go straight out and not in the corners), according to figure 3. b. This effect is so pronounced in some event scenarios that using a probability distribution with zero azimuthal (cross) variance can result in severe underestimation of fragment density and maximum throw distances along the normal direction.

When using the distribution function model (e.g. Gaussian normal distribution) taking into account the azimuthal variation, the value of the standard deviation, σ is a measure of the angular dispersion of the analyzed material fragments, which can be determined using the limit value of this value.



b. Shape and dispersion (fourfoil-shaped) of material fragments

Figure 3. Detailing the probability density function and the dispersion mode of fragments

The probability density of material fragments resulting from the detonation of explosives is characterized as a function of the range of the throw distance (r) and the scatter angle (θ) along the direction normal to the wall of the structure. Both the distance r and the angle θ are treated independently according to the mathematical model associated with the fragment projection effect (1):

$$f_{f_1, f_3} = f_{1,2}(r) * f_3(\theta), \quad (1)$$

$$f_1(r) = A_1 + A_2 r + A_3 r^2 + A_4 r^3, \quad (2)$$

From the initial conditions it follows:

$$\begin{aligned} A_1 &= Y_0; A_1 + A_2 R_{Y_{\max}} + A_3 R_{Y_{\max}}^2 + A_4 R_{Y_{\max}}^3 = Y_{\max} \Leftrightarrow \\ Y_{\max} - Y_0 &= A_2 R_{Y_{\max}} + A_3 R_{Y_{\max}}^2 + A_4 R_{Y_{\max}}^3; \quad 2A_3 R_{Y_{\max}} - 3A_4 R_{Y_{\max}}^2 = 0, \end{aligned}$$

$$\begin{bmatrix} R_{Y_{max}}^2 & R_{Y_{max}}^3 \\ R_{Y_{max}} & R_{Y_{max}}^2 \end{bmatrix} \begin{bmatrix} A_3 \\ A_4 \end{bmatrix} = \begin{bmatrix} Y_{max} - Y_0 \\ 0 \end{bmatrix}, \quad (3)$$
$$J^{Ea} = J * 0,997 * c/S_1, \quad (4)$$

With relation (4), the normalized values A_1' , A_2' , A_3' and A_4' are calculated, and S_1 is determined by integrating the function $f_1(r)$, on the domain delimited by $r=[0, R_{Y_{max}}]$, respectively:

$$S_1 = \int_{r=0}^{r=R_{Y_{max}}} f_1(r) dr = \int_{r=0}^{r=R_{Y_{max}}} (A_1 + A_2 r + A_3 r^2 + A_4 r^3) dr = A_1 R_{Y_{max}} + \frac{A_2}{2} R_{Y_{max}}^2 + \frac{A_3}{3} R_{Y_{max}}^3 + \frac{A_4}{4} R_{Y_{max}}^4 \quad (5)$$

To prevent slope discontinuity at the peak of the distribution, using the fitting polynomial described earlier is extended beyond the peak of the distribution by a percentage $d(\%)$, of the distance from the peak to the maximum throw interval, as set by user input, the value of d is currently set to 10%, in which case the adjusted range delimitation is done for $r=[0, R_{Y_{max}} + d \cdot (R_{MT} - R_{Y_{max}})]$.

The second branch of the distribution function is explained by an exponential type model, of the form:

$$f_2(r) = k_1 e^{k_2 [r - R_{Y_{max}} + 0,1(R_{MT} - R_{Y_{max}})]}, \quad (6)$$

The determination of the two coefficients k_1 and k_2 is done respecting the following conditions: $f_1(r) = f_2(r)$, for $r = [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})]$; the area under the curve $f_2(r)$, for $r = [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}}), R_{MT}]$ represents the true density of fragments projected at distance R_{MT} . From the first condition it follows that $k_1 = Y_{max}$, for $r = [0, R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})]$.

To apply the second condition and to determine k_2 , the area under the $f_1(r)$ curve from the center to $r = [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}}), R_{MT}]$. Taking into account both coefficient scaling and domain expansion, this area is expressed as:

$$S_{f1} = \int_{r=0}^{r=R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})} f_1(r) dr = \int_{r=0}^{r=R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})} (A_1 + A_2 r + A_3 r^2 + A_4 r^3) dr \quad (7)$$

$$S_{f1} = A_1 [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})] + \frac{A_2}{2} [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})]^2 + \frac{A_3}{3} [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})]^3 + \frac{A_4}{4} [R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})]^4 \quad (8)$$

The area under the curve $f_2(r)$, for $r = [R_{Y_{max}}, R_{MT}]$ is given by the expression :

$$S_{f2} = 0,9973 - S_{f1}, \quad (9)$$

The coefficient k_2 is determined so that:

$$\int_{r=R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})}^{R_{MT}} f_2(r) dr = S_{f2}, \quad (10)$$

$$S_{f2} = \left[\frac{R_{Y_{max}} + 0,1 \cdot (R_{MT} - R_{Y_{max}})}{k_2} \right] e^{k_2 [R_{MT} - R_{Y_{max}} - 0,1(R_{MT} - R_{Y_{max}})]}$$

Finally, the probability density function $f_{1,2}(r)$ is of the form:

$$f_{1,2}(r) = \begin{cases} f_1, & \text{for } r = [0, R_{Y_{max}}] \\ f_2, & \text{for } r = [R_{Y_{max}}, R_{MT}] \end{cases} \quad (11)$$

Determining the function $f_3(\theta)$

The variation of the probability density as a function of the angle θ to the wall normal direction of the structure is modeled using a normal distribution with the center located on the wall normal direction and the standard deviation σ_θ . The value of σ_θ is determined from the results of tests carried out on different amounts of explosives and types of material specific to resistance structures (concrete or steel). Also, the distance along the transverse arc is R_θ , and the standard deviation expressed as a distance is R_{σ_θ} .

Thus, the function $f_3(\theta)$ has the form:

$$f_3(\theta) = \frac{1}{2\pi R_{\sigma_\theta}} e^{-0,5 \left(\frac{R_\theta}{R_{\sigma_\theta}} \right)^2} = \frac{1}{2\pi R_{\sigma_\theta}} e^{-0,5 \left(\frac{\theta}{\sigma_\theta} \right)^2}, \quad (12)$$

To preserve the relative amplitudes of the downward variation of the probability density along the central direction, it is desirable that the angular variation of the probability density be a function of the variable θ . This is done by using a constant, characteristic value of R in the function expression $f_3(\theta)$. Thus, the centroid of the

downward-facing distribution R_c , is selected as the constant range to use in the angular calculation and $f_3(\theta)$, becomes:

$$f_3(\theta) = \frac{1}{2\pi R_c \sigma_\theta} e^{-0.5 \left(\frac{\theta}{\sigma_\theta} \right)^2}, \quad (13)$$

To determine R_c proceed as follows:

$$R_c = \frac{\int r * f(r) dr}{S_{total}} = \frac{\int r * f(r) dr}{0.9973} = \frac{\int_{r=0}^{r=R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})} r * f_1(r) dr + \int_{r=R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})}^{r=R_{MT}} r * f_2(r) dr}{0.9973} \quad (14)$$

$$R_c = \frac{A_1^{Ea}}{2} [R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})]^2 + \frac{A_2^{Ea}}{3} [R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})]^3 + \frac{A_3^{Ea}}{4} [R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})]^4 + \frac{A_4^{Ea}}{5} [R_{Ymax} + 0.1 * (R_{MT} - R_{Ymax})]^5 + \frac{Y_{max}}{k_2^2} \{ (k_2 R_{MT} - 1) e^{[k_2 R_{MT} - k_2 R_{Ymax} - k_2 0.1 * (R_{MT} - R_{Ymax})]} - k_2 R_{Ymax} - k_2 0.1 * (R_{MT} - R_{Ymax}) + 1 \} \quad (14')$$

Figure 4 shows the results of an example of modeling the design effect of fragments of material resulting from the detonation of explosive materials, using the previously defined probability distributions, characterized by the following data: $a=0.33$; $b=0.038$; $c=50\%$; $d=10\%$; $X_{MT}=579m$; $\sigma=20^\circ$. In each figure, the zero point located on the direction normal to the wall of the structure is identified by a circle.

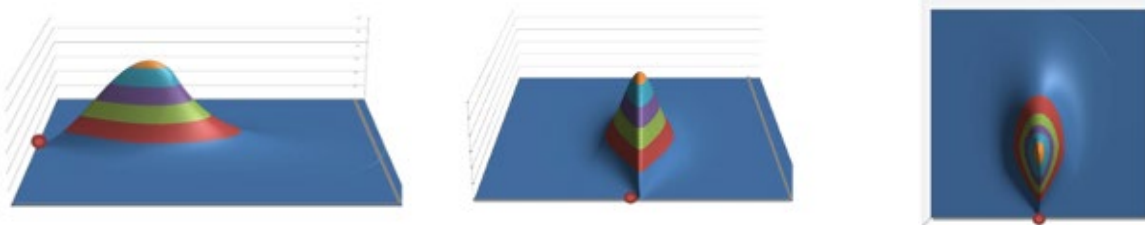


Figure 4. Results of modeling the throw effect of material fragments in the wake detonation of explosive materials

The results of the computer modeling presented graphically in figure 4 confirm the principles underlying the configuration of probability density functions, respecting the conditions imposed by mathematical laws, in close correlation with the most faithful reproduction of reality regarding the analysis of event scenarios when explosive materials are involved, from the perspective of evaluating the design effect of fragments of material resulting from the detonation of these types of products.

5. Assessment of the degree of injury following the impact with material fragments resulting from the detonation of explosive materials

The graph-analytical tool for assessing the degree of damage following the impact with material fragments resulting from the detonation of explosive materials is based on the use of the simplified mechanism of fatality caused by an event of the explosion type following the detonation of explosive materials (MSFEXP) whose particular mode of application is represented graphically in figure 5. Within the hazard mechanism generated by the dispersion of material fragments, highlighted in the MSFEXP model, customized for the case of this scenario (fig. 5), the parameter $P_{d/e, material fragments}$ can reach a value of 1.0 if the manifestation of the explosion-type event takes place in the plateau area, the transition area being non-existent because $X_1 = X_2$. Also, $P_{d/e, material fragments}$ is equal to 1.0 if the ES-type exposure structure is located from the PES-type explosive structure at a distance less than twice the radius of the crater formed by the detonation of the explosive materials.

Within this model $P_{d/e, fragmente materiale}$ represents the probability of lethal damage to a person, following the impact of hitting with a material fragment resulting from the detonation of explosive materials. Similarly, using the methodological reasoning of the model, the probabilities of occurrence of major injuries can be determined ($P_{majl, material fragments}$) and of minor injuries ($P_{minl, material fragments}$) caused by projected material debris.

The number of fragments that can hit an ES exposure structure is quantified in the form of a density of material pieces, expressed in fragments/unit area, which together with their final velocity and mass, lead to the determination of the related kinetic energy value.

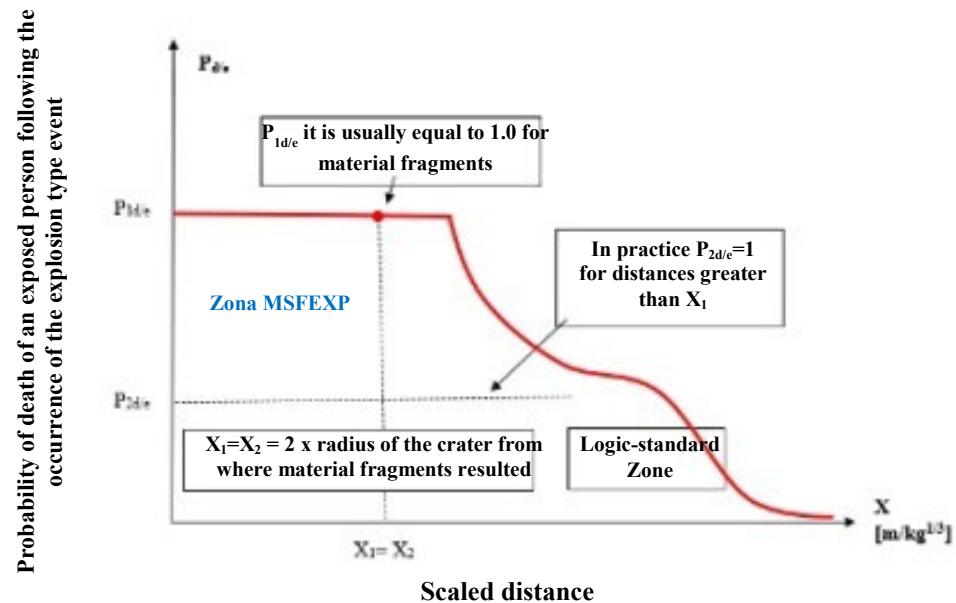


Figure 5. The simplified fatality mechanism customized for the effect of dispersion of material fragments

6. Conclusions

The fractional damage to the structure that remains intact after an explosive event is a function of the equivalent net explosive weight and the type of building. In this regard, the fractional damage (characterized by a value between 0 and 1) of each component (roof, front wall, side walls and rear wall) is determined by comparing the net explosive weight equivalent to the damage limits at the lower and upper limits for different types of structures.

The analytical tool for modeling the dispersion of material fragments from explosions was configured based on the explosion risk model, using established probability density functions for evaluating the design effect of material fragments following the detonation of explosive materials (Gaussian distribution, toroidal distribution without variation azimuthal, distribution with non-zero azimuthal variation).

The number of fragments that can hit an exposure structure is quantified in the form of a density of material pieces, expressed in fragments/unit of area, which together with their final velocity and mass, lead to the determination of the value of the related kinetic energy.

The material fragments that have different angles (large and small) of dispersion, as well as those that make a side impact, have their own final velocities at the moment of hitting the exposure structure, while for the concrete material fragments and those from the crater formed after explosion, the kinetic energy class is determined according to their mass, and in the case of steel fragments, a higher energy class is chosen due to their increased speed from the moment of impact.

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