Assessment of the throwing effect of material fragments resulting from the detonation of explosive materials

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Abstract. The modelling of the throw effect of material fragments following the detonation of explosive materials with a harmful effect on the human component and/or nearby industrial/civil targets is based on the quantification of the impact of the throwing speed and mass of the material fragments. 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 time intervals to run the simulations at the time of analysis and IT resources to match. Following the production of an explosion-type event, thousands of individual fragments characterized by their own mass and velocity parameters can be generated, resulting individual energy values that can be taken into account in a quantitative risk assessment, by grouping them into ten distinct classes, thus: Class 1st represents fragments with the highest kinetic energy and/or mass, and class 10th represents fragments with the lowest kinetic energy and/or mass. The paper will highlight the ten distinct classes of the kinetic energy parameter, with the maximum, average and minimum values for each class, as well as the average mass for each detached fragment associated with the energy classes.

1 Overview of how pieces of material break off when explosive charges go off

A detonation is a physical and chemical process that is characterized by a quick response speed and by the synthesis of vast volumes of gases at high temperatures. The detonation mechanism can be broken down into three distinct steps, which are as follows: I. The mechanical compression of each molecule of the explosive substance brought about by a

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dynamic pulse; II. The thermal decomposition of each layer in the structure of the explosive, up to high temperatures, when given the rapidity of the chemical reaction, the dynamic compression process being carried out without heat exchange in the environment (adiabatic compression); III. The exo-thermal decomposition of the explosive as a result of the action of high temperatures [1].

When holes are made

A simplified representation of the crater left behind by the explosion of an explosive charge is shown in figure No. 1. The following are some of the dimensions that are related with craters: D2 represents the crater's apparent diameter, whereas D1 represents the crater's true diameter. h1 represents the crater's actual depth, and h represents the height of the berm.

The explosion of explosive charges that have been positioned in the following manner causes the formation of craters: Positions include below ground level (in a closed area), on the ground (at the air-ground interface), and in the air. The destructive impact of a blasting is the formation of a crater, and this occurs regardless of the placement of the explosive charge. When the explosive charge is set off, a powerful decomposition reaction takes place in its mass [2].

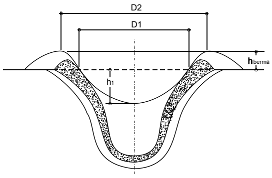

Fig.1. How to measure the size of a hole

Material from an explosion can be broken down into three types of pieces: main, secondary, and scrap from the crater that was made. Most of the pieces come from where the explosive went off and from the structure of the storage room, like the top, end walls, side walls, and back wall. Also, when the impact crater forms, pieces of the ground or the base structure of the storage room are left behind. In the case of an explosion, there could be thousands of separate pieces that can be identified by their mass, speed, and kinetic energy. The model type QRA (Quantitative Risk Assessment), which is dedicated to quantitative risk assessment, allows for a study of the whole volume of designed fragments based on a dynamic model of meshing the mass and using the distribution pattern of recurrent Bin n, (1). to give an overall look at the 10 types of results (Bin_i, i=1,10).

$$Bin\ n: DAM_n = RM_n + \left(\sum_{i=1}^{n-1}\left(DM_{[i,n]}\right)\right) + \left(\sum_{i=2}^{n-1}\left(B11DM_{[i,n]}\right)\right) \tag{1}$$

where: DAM stands for "dynamic adjustment of the material fragment's mass"; RM stands for the amount of leftover material in a fragment; DM stands for the amount of leftover material in a fragment.

So, Bin1–Bin10 shows the pieces that have a high/low mass and a high/low amount of damage and/or destruction to humans and/or structures. Table 1 shows the results for the ten classes (Bin1–Bin10) based on the level of damage/destruction (via kinetic energy) at the odds of maximum, medium, and minimum, as well as the average weight of each fragment created based on the type of material.

Table 1. Results for the ten classes (Bin1–Bin10)

Class (Bin_{in} n=1,10)	**Bin_1**	**Bin_2**	**Bin_3**	**Bin_4**	**Bin_5**	**Bin_6**	**Bin_7**	**Bin_8**	**Bin_9**	**Bin_{10}**

Minimum kinetic energy (m-Kg)	100K	30K	10K	3K	1K	300	100	30	10	3
Average kinetic energy (m-Kg)	173K	54K	17K	5K	1,7K	547	173	54	17	5
The maximum kinetic energy (m-Kg)	≥300K	100K	30K	10K	3K	1K	300	100	30	10
The average weight of fragments of steel (Kg)	16,19352	6,75864	2,875824	1,206576	0,512568	0,214553	0,090266	0,038647	0,017191	0,006441
The average weight of concrete fragments (Kg)	34,20144	14,2884	6,07824	2,544696	1,079568	0,4536	0,190512	0,081648	0,036288	0,013608

An explanation of the main pieces

The main fragments are made by explosive destruction and packaging after the explosion. Their design is based on the number of fragments, their weight, and the distance they can be thrown the farthest. (Figure no.2). The relationship tells us how many explosive goods there are (N_w) (2) [3].:

$$N_W = \frac{W_1}{NEWQD\ of\ one\ explosive\ article} \tag{2}$$

where W_1 is the amount of explosives in the first explosive product, NEW is the amount of explosives left over after making the first product, and QD is the distance based on the amount of explosives.

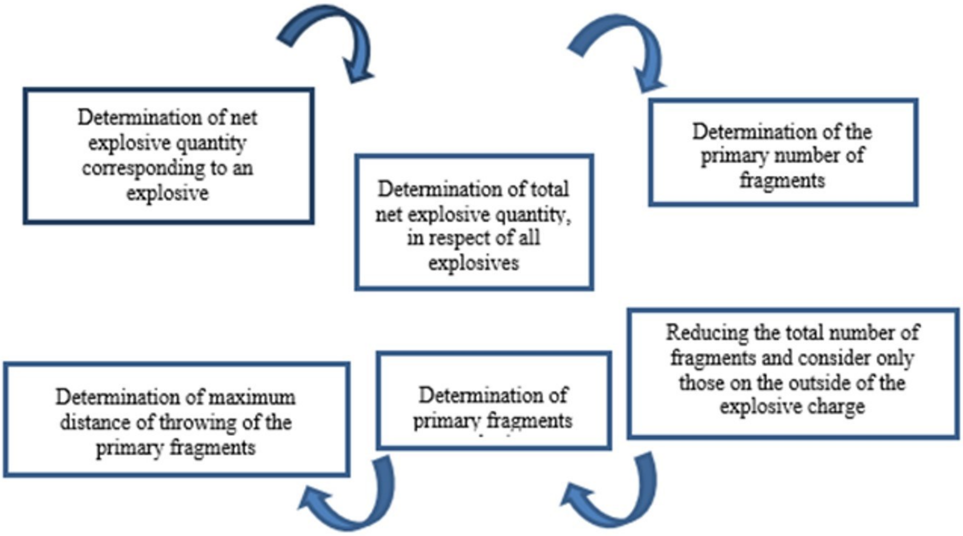

Fig.2.Diagram of how the main fragments are projected

Table 2. Results

Explosive charges	**NEW specific for a single type of explosive product (Kg)**	**Fragments derived from a single product**									
		Mass Bin$_n$, n=1÷10									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
explosive charges with small fragments	0,4536	0	0	0	0	0	0	0	1	5	10
Explosive charges without primer fragments	0,4536	0	0	0	0	0	0	0	0	0	0
metallic container with explosive charge	4.536	0	0	0	0	0	0	80	4.111	796	319
Explosive charge confined in the metal pipe	3,901	0	0	0	0	0	0	4	19	44	79

Also shown in tables are the highest range values of action/projection of the primary fragments (R_{max}), which are calculated for each fragment based on its average weight, the appropriate bin, and its initial rate. (Table 3).

Table 3. The highest range values of action/projection of the primary fragments

explosive charges	**V (m/s)**	**R_s(m)**	**R_M(m)**
explosive charges with small fragments	1219,2	569,976	683,9712
Explosive charges without primer fragments	NA	NA	NA
metallic container with explosive charge	1219,2	569,976	683,9712
Explosive charge confined in the metal pipe	1219,2	569,976	683,9712

Also shown in tables are the highest range values of action/projection of the primary fragments (R_{max}), which are calculated for each fragment based on its average weight, the appropriate bin, and its initial rate.

In the case of an explosion, the product inside a potentially explosive structure of type PES (used to store explosives for civil uses) breaks into a large number of primary fragments whose number and starting speed are based on the data in tables 2 and 3. Also, the parts of the PES structure that are still there after the blast can block and get rid of the main pieces that were made by this event. At the same time, it's important to figure out how much of the main fragment is blocked by the roof, front wall, back wall, and side walls of the PES.

So, in order to figure out how many primary fragments may be blocked by different parts of the PES's structure, they must be split into two groups based on the angle at which they are thrown: those that hit the roof and those that hit the walls. The bottom angular pieces, in turn, are split into side impact pieces and horizontal pieces that have moved in a nearly horizontal direction. Also, side-impact pieces have an arched path to an ES-type structure, which is a structure that is vulnerable to an explosion The main fragments are separated into three groups: high-angle fragments, side-impact fragments, and horizontal fragments. High-angle fragments make up 25% of the total number of fragments, while side-impact fragments make up 7.5% and horizontal fragments make up 67.5%. Setting these numbers is based on how test data, such as high-speed video analysis, is interpreted. The main fragments are broken up into pieces that each structure type PES can block or hold. Side impact fragments and horizontal fragments might be stopped by the front wall, sidewalls, and components of the back wall structure type PES.

2 Estimation of the density of the material pieces

Estimating the path that the thrown material took can be done by using the results of different research projects in this field. It also requires a good understanding of the science behind the main parameters that are evaluated, which are the speed of impact and the mass of the material fragment thrown. It would be best to use physical laws based on differential equations that describe wave phenomena to figure out where and how fast each piece of debris hits the ground. At the moment, however, there are no scientifically proven answers for a specific scenario that involves an explosion. Where test results of explosives accident numbers and validated simulation data are available, type models called Fast-Running Models (FRMs) can be used to analyze hazards in a simpler way than using difficult, complex physical models based on the equation of state. So, as of now, American science (type FRMs) has developed specialized software in the field of explosives for civil uses called IMESAFR 2.0. It uses different probability density functions (PDFs) that are specific to this field to make a graphic-analytical model of the phenomenon of projecting pieces of material that happen when an explosion happens. This PDF is made by preprocessing, simulating, and/or analyzing test data in a specialized equation (closed form). Once the density function has been set, it can produce results right away. In Figure No. 3, a number of data points that have been turned into a closed-form equation show an example of computer test data. This PDF is a contour map that shows almost instantly what parts of the material density are expected to be. It can be made with different levels of complexity so that it can be used to show different types of models based on probability density functions. So, PDFs are made up of "down-range" elements and "cross-range" elements. "Down-range" component re-creates the shape of the blast's start in any direction around it. This important part sets the distance between the original place where the explosive charge goes off and the design parts of the material and the range of their greater density. Cross-range component determines the shape of the tool when it moves in a radial direction at a constant distance from the center (cross-range). In the next section, we'll talk about the two parts of the PDFs modeling method that is often used to keep explosives safe [4].

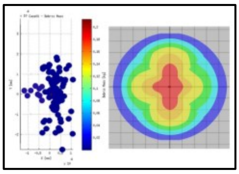

Fig.3. An example of how test results can be turned into a PDF (the dispersion of the resulting dangerous fragments)

The most usual PDFs are the ones that are the same in all directions from the center (that is, they don't change in the direction of travel). These distributions can be used to model safety in a good way if they are evenly spread out or random in all directions around the site of an explosion. For example, pieces of material that are thrown up and spread out when the roof blows off, as well as pieces of wall structures with different arcuate shapes. The first example is a function of the type Gauss-normal of distribution (like a bell-shaped curve) used as a component "down-range" without any change in azimuth. This makes a distribution parameter of the type bi-variant Normal (BVN), which looks like a hill with the largest density at the origin (Figure 4).

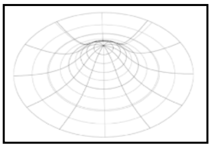

Fig.4. Bi-Standard version (BVN) is the type of distribution

The following equation shows how PDF- looks for the distribution of BVN:

$$P_i = \frac{1}{2\pi\sigma^2} e^{\left(\frac{-\gamma^2}{2\sigma^2}\right)} \tag{3}$$

where: P_i - Chance that a single piece will land in a certain area; σ - The standard deviation of the distance "down-range"; r - Start at the beginning and end at the point of interest

The ISURF model

Probability density BVN is useful for proving the basic scenarios when there aren't a lot of data and information available. In this case, it is assumed that the danger of flying pieces of material is higher near the blast origin for the production site, where the charging material exploded. But there may be times when a lot of the pieces are thrown away from where they came from. This is especially true for primary fragments, which are the pieces left over from the explosive charge, and secondary fragments, which are parts of wall. When the "BVN down-range" model is used in these kinds of situations, the problem with the PDF is that it overestimates how many fragments will be thrown near the start in small amounts at regular intervals. The Institute of Explosives Manufacturers (IME) did research to create a specialized computer infrastructure for the security of explosives (IMESAFR). Research APT came up with a new function called "down-range" to improve the "BVN down-range" model, which led to a "toroidal PDF with azimuthal variation (Figure 5) [5].

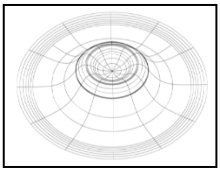

Fig.5. PDF toroidal, no change in direction, type ISURF

Comparative analysis of the two established models for proving the scenarios of projecting the fragments of material that result from the explosion of explosive charges, Curve BVN down-range and Curve PDF toroidal down-range, shows that the areas occupied by the two curves are the same, which means that they roughly represent the same amount of total mass of the projected fragments.

The ISURFGAD model

This model has a zero change in azimuth, which means that the results are the same in all directions. It is used to model a uniform hazard in any direction, including fragments falling from the roof, the circular crater effect at explosives warehouses, and explosions in which pieces are thrown in random directions. Because debris tends to "move along the normal" and not in the "corners" when loads are in the center of rectangle buildings, it has been seen that the azimuth has a big effect on how dense the thrown material is. making a type of effect Cloverleaf (PDF with angle zero – transversely range) is shown in Figure 6. Figure 7 shows a new type of PDF (ISURFGAD) that is based on a model of transverse range and takes into account this kind of effect.PDF type ISURFGAD is done separately for the "down-range" function and the "transverse radius." The function is shown for one dial of 900, probability density of the parts of the material by independent factors, respective interval of the range (r) and the throwing angle (θ), so [6]:

$$PDF = f(r) * g(\theta) \qquad (4),$$

in which:

$f(r) = f_1 = A' + B'r + C'r^2 + D'r^3$, out of range $[0, R_{P+}]$,

$f(r) = f_2 = k_1 \exp[k_2 * (r - R_{P+}]$, out of range $[R_{P+}, R_{max}]$

$g(\theta) = [1/(2\pi R_c \sigma_\theta)] \exp[-0{,}5(\theta/\sigma_\theta)^2]$

where: R_{p+} - Chance density's highest point; R_{max} - The highest distance that parts of the material can be thrown; R_C - the centroid radius

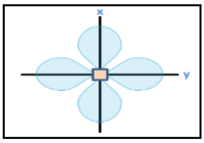

Fig.6. The Cloverleaf model shows how the pieces of material are spread out

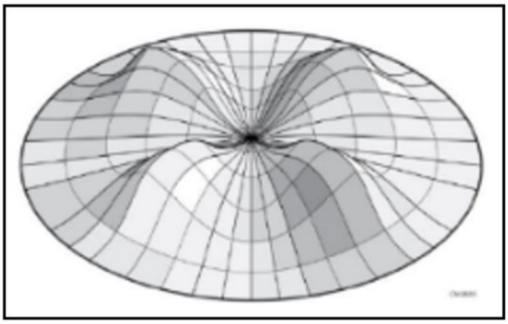

Fig.7. New ISURFGAD in PDF form

3 Human vulnerability estimate based on the effects of parts of the material created when explosive charges go off

In earlier sections, we talked about the technical aspects of modeling parts of the material that come from the explosion of explosive charges from structures of type PES (for storing explosives), which can destroy structures that are exposed to explosions of type ES (for specific activities), which can have serious effects on the health and safety of staff and the people who live nearby. For modeling the amount of damage to the human component using a probability equation set up based on the Poisson probability distribution (5), different [7]:

$$P_{impact} = 1 - e^{-EN^*} \tag{5}$$

where: E - human exposure (0.278 m^2); N* - number of pieces that could hurt the purity of the human component

For solving the probability equation, the model gives an estimate of the number of deaths and major and minor injuries in areas based on the speed of the fragments that are forecast (6):

$$P_{f(d)} = \text{Lethality value x } P_{hit} \tag{6}$$

Figure 8's curve shows the relationship between the probability of death for an event Pf|e and the kinetic energy of the pieces that are thrown. This gives us the lethality value. Lastly, the model figures out the overall probability of death caused by projected fragments (Pf(d)) by adding the paths of the large fragments' angular projections and the displacements of the small fragments' angular projections. The total probability of death is found by using the additive rule for events that don't cancel each other out:

$$P_{f(d)} = P_{f(d)\text{low-ungle}} + (1 - P_{f(d)\text{low-ungle}}) \text{ x } P_{f(d)\text{high-ungle}} \tag{7}$$

where: $P_{f(d)}$ - chance that a person will die because of a hit with a fragment

The chance of major damage/minor injuries (Pmaji(d)/Pmini(d)) is calculated in the same way. To prove how dangerous the mechanism of pieces being thrown is, we're using a pattern called SCIFM (Simplified Case-In Fatality Mechanism) to look at all the possible situations that could happen (Figure 9).

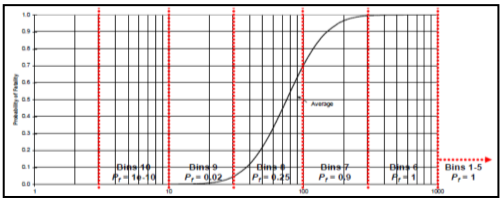

Fig.8. The chance that a person will be exposed to kinetic energy

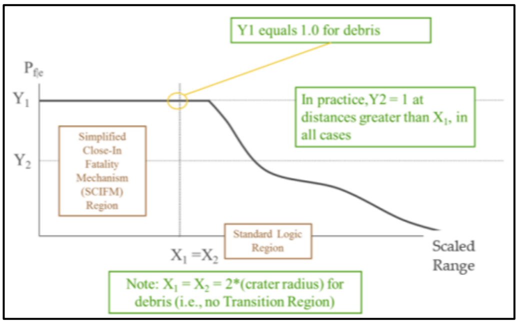

Fig.9. The SCIFM model for projecting pieces

4 Examples of how the methods shown can be used

Figure 10 shows an example of a surface PDF with the following values: a = 0.330, b = 0.038, c = 50%, d = 10%, maximum range extension = 579 m, and = 200.

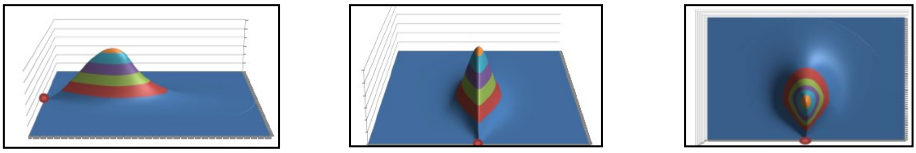

Fig.10. PDF surface - ISURFGAD PDF

The results of modeling the risk of injury from thrown pieces of material from an explosion can be shown in a graphic-analytical way. These results can be seen in Figure 15's diagrams of the destructive capacity of the thrown pieces (kinetic energy of impact from thrown pieces of material) and in Figure 11's histograms of the probability values of damage to the human component.

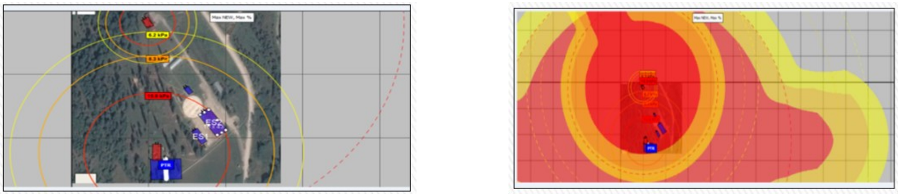

Fig.11. Contour map of an explosives depot that can hold 1220 kg ETNT (overpressure curves and dispersion of the resulting hazardous fragments)

Figures 11 show the results that are needed to find the areas of interest in the event of an explosion caused by the discharge of explosive charges. This leads to the following planning areas: The area of high mortality is one in which about half of the exposed population dies. The area of irreversible injuries is one in which about half of the exposed population suffers serious damage to the body and lungs, serious illness, and first- and second-degree burns. Light houses take a lot of damage and can't be used. Heavy structures can get minor damage; the "attention area," which is the distance from the accident where the effects can be felt, can cause a mild sickness that lasts only a short time or minor burns that are easy to treat. When accidents involving explosions happen, light buildings in the area may get minor harm.

5 Conclusions

5.1. Using model type Fast-Running Models (FRMs), which were made for simplified hazard analysis by using different probability functions designed for this area (like model type ISURFGAD with the azimuthal variation), it is possible to estimate the route configuration of the fragments of material that are projected as a result of explosion-type events. The model for figuring out where the debris from an explosion will go takes into account three kinds of pieces: main, secondary, and scrap from the area where the crater was.

5.2. This paper has talked about the technical aspects of modeling material fragments caused by the explosion of explosive charges coming from potentially explosive structures, type PES (for storing explosive materials), which can destroy structures exposed to explosions, type ES (for specific activities), with serious effects on the health and safety of workers and people living nearby. The final results of modeling the risk of injury from the projection of material caused by an explosion can be shown graphically and analytically through diagrams of the contour map and histograms of the probability values of damage to the human component (death, major injuries, and minor injuries).

Acknowledgements

This work was carried out through the" Nucleu" Program within the National Plan for Research, Development, and Innovation 2022-2027, with the support of the Romanian Ministry of Research, Innovation and Digitalisation, project no. 23 32 02 03, title: Development of monitoring methods to reduce environmental impact from the use of explosive materials, pyrotechnic articles, and application of blasting technologies.

Bibliography

1. Hardwick, Meredith, Hall, John, Tatom, John, and Baker, Robert, *Approved Methods and Algorithms for DoD Risk-Based Explosive Siting*, DDESB Technical Paper 14, 21 July 2009.

2. Arnauld, A. and Nicole, P., *Logic or the Art of Thinking*, 1996.

3. Pfitzer, T., *Use of Fatality as the Measure of Risk*, Tech Memo E1-00300, A-P-T Research, Inc., Huntsville, AL, May 8, 2002.

4. Institute of Makers of Explosives Safety Analysis for Risk - *User's Reference Manual*, Version 2. October 2014.

5. IMESAFR P(e) Matrix Tech Memo, *APT Report CM-07400*, May 2006.

6. RCC Standard 321-00, *Common Risk Criteria for National Test Ranges*; Inert Debris, published by Secretariat, Range Commanders Council, US Army White Sands Missile Range, New Mexico 88002-5110, April 2000.

7. "*RBESCT Technical Issues Regarding Injury Modeling*," APT CE3-00300, 26 February 2004.