RECENT DEVELOPMENTS OF THE KG SOFTWARE

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Abstract

Explosive loading of a reinforced concrete ammunition magazine may result in break-up and launch of debris. Since debris throw is one of the major hazards in case of an accidental explosion, it is of high importance within risk assessment tools. Within the Klotz Group this phenomenon has been modelled and implemented in the KG Software. The software is based on state of the art knowledge and experimental data from full scale trials. A number of new features are currently being implemented in two projects sponsored by the KG, and conducted by TNO and EMI. This paper describes and illustrates these features with examples.

A number of these new features is related to risk assessment application. The first one is the possibility to define a sloped terrain, to enhance the applicability of the software in various countries. Furthermore, the possibility to calculate the number of hits at user-defined exposed sites, and the possibility to specify barricades have been added.

In addition to these new features, the paper also addresses the improvement of the debris trajectory prediction. Conventional models describing the flight of debris are based on the assumption of individual debris motion. However, the debris cloud originating from a reinforced concrete wall is initially very dense. As a result, debris trajectories can not be considered independently at these stages. Comparing conventional models with experimental data has shown that small debris requires unrealistic high launch velocities to reach the observed pick-up distances. The developed ‘ballistic filtering’ model gives a more realistic description of the initial stages of debris throw. The model has been implemented in a research version of the KG Software and has been compared to trial data.

1. Introduction

Explosive loading of a reinforced concrete ammunition magazine may result in break-up and launch of debris. Since debris throw is one of the major hazards in case of an accidental explosion, it is of high importance within risk assessment tools. The Klotz Group (KG) has asked TNO Defence, Security and Safety and Fraunhofer Ernst-Mach-Institute (EMI) to develop the KG Software. This has been carried out in two joint projects in 2007 and 2008. With this software tool the debris hazard from RC structures in the event of an internal detonation can be quantified. The KG Software is the result of state of the art knowledge and available test data from a number of trials.

The KG Software is based on the KG Engineering tool (Van Doormaal, 2006) and the source function theorem formulation of the debris distribution (Van der Voort, 2008). The KG Engineering tool describes the distributions of debris mass, launch velocity and launch angle in dependence of the loading. These have been obtained by means of backward calculation. The source function theorem is an efficient method to derive the debris density from trajectory calculations. The calculation kernel has been developed by TNO (Van der Voort, 2007) and the user interface including a backward calculation module by EMI (Pfanner, 2007).

A typical output screen of the KG Software is shown in Figure 1, illustrating a top view of a typical throw pattern (debris density in horizontal plane). Output is generated for the 10 Sci Pan mass bins, and can be presented individually or accumulated. Besides the debris density, the impact angle, impact velocity and impact energy can be presented.

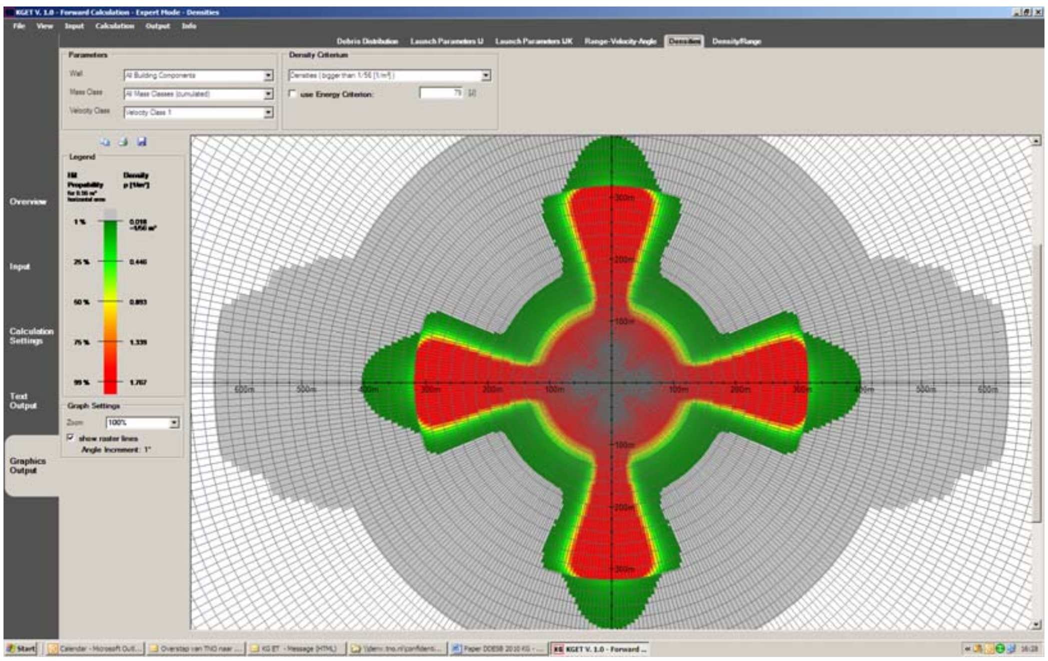

Figure 1. KG Software v1.0 output screen with a top view of the debris density

The development of the KG Software has been reported in a large number of papers over the last years, as listed in the references (DDESB Explosive Safety seminar in 2006 and 2008 and ISIEMS in 2007). The KG Software has also been described in the NATO manual AASTP-4, 2008.

This paper describes a number of new features which are currently being implemented in the KG Software. The first three are related to risk assessment application (Van der Voort, 2010-1). These are:

- The possibility to determine the influence of a sloped terrain
- The possibility to take the influence of a barricade at either the PES (Potentially Explosive Site) or the ES (Exposed Site) into account
- The possibility to determine the number of hits at a predefined ES

These extensions involve adaptations in both the calculation kernel and the user interface, and are described in Section 2, 3 and 4, respectively. Figure 2 gives an impression of the model input required for these new features.

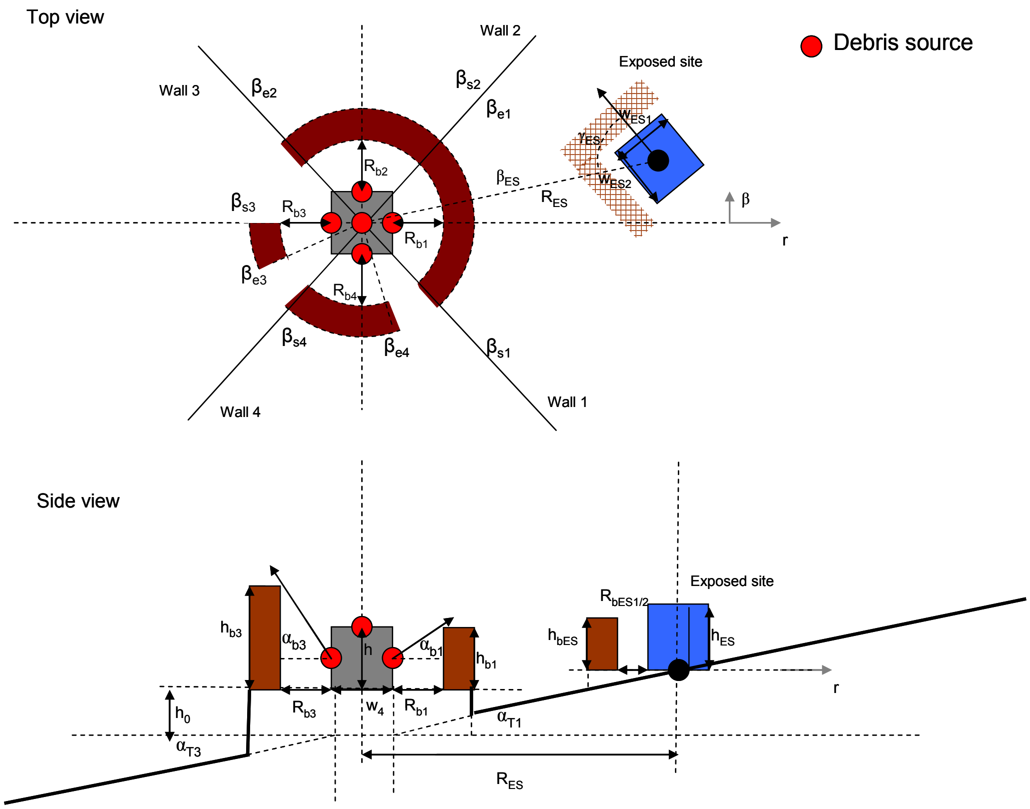

Figure 2. ***Overview of new input for the KG Software v1.0 related to sloped terrain, barricades, and number of hits (top view and side view respectively).***

Furthermore, areas for improvement have been identified in relation to the trajectory calculations. The KG Software v1.0 predicts unrealistic high launch velocities for small debris. This is the result of an inadequate physical description of the initial stages of debris motion. In this regime a dense debris cloud is present, and the mutual influence of the debris has to be taken into account. As an alternative the 'ballistic filtering' model has been proposed (Van der Voort, 2010-2). This model is described in Section 5 and has been implemented in a research version of the KG Software. The model is compared to experimental results, and the assumptions in the model are optimized. A decision whether the ballistic filtering model should be included in a new version of the KG Software will be taken during the KG Fall 2010 meeting.

For the long term the KG aims to further extend the KG Software with models for the interaction of primary fragments from cased ammunition with the RC structure. Experimental and numerical research in this area is currently being carried out. Also other types of storage structures are of interest, such as ISO containers. The status of the research in this area is presented by (Tatom, 2010).

2. Sloped terrain

The first new feature is the possibility to determine the influence of a sloped terrain, in order to enhance the applicability of the software in various countries. For each of the four sides of the PES (j=1..4) a fixed terrain slope α_{Tj} has to be entered between -45° and 45°. The impact distances are determined as follows. Each debris trajectory is linearized between time step 'n-1' (just above the slope) and time-step 'n' (just below the slope). The impact distance is then obtained as the intersection r* between the linearized trajectory and the slope (Figure 3):

$$r^* = \frac{z_{n-1} \cdot (r_n - r_{n-1}) - r_{n-1} \cdot (z_n - z_{n-1})}{\tan(\alpha_{Tj}) \cdot (r_n - r_{n-1}) - (z_n - z_{n-1})} \quad (1)$$

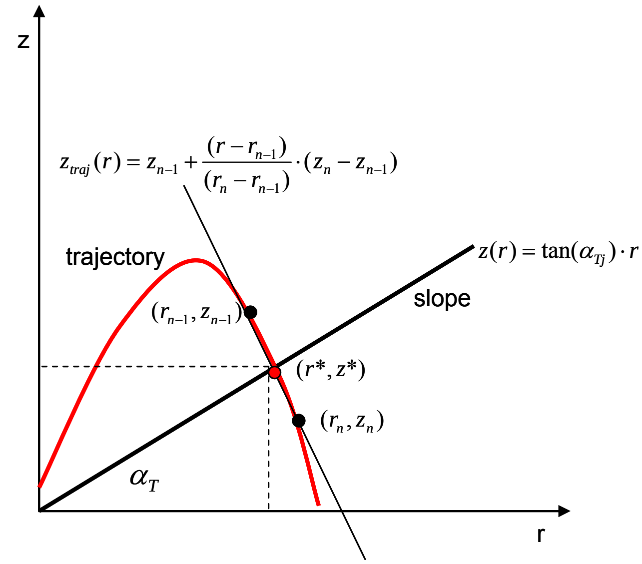

Figure 3. ***Illustration of numerical method for determination of the impact distance.***

The impact distances are measured along the radial direction (r) in the horizontal plane, i.e. not along the slope itself. The debris density and impact angle are calculated for a locally horizontal surface, i.e. as seen from above. This is realistic since exposed sites on a slope are also always placed on a locally horizontal surface! Figure 4 shows that the impact angle at the bottom of the exposed site geometry is always negative for negative slopes (downhill). This observation is expected to hold true for all impacts on small exposed sites for realistic geometries. For positive slopes (uphill) both positive and negative impact angle are possible.

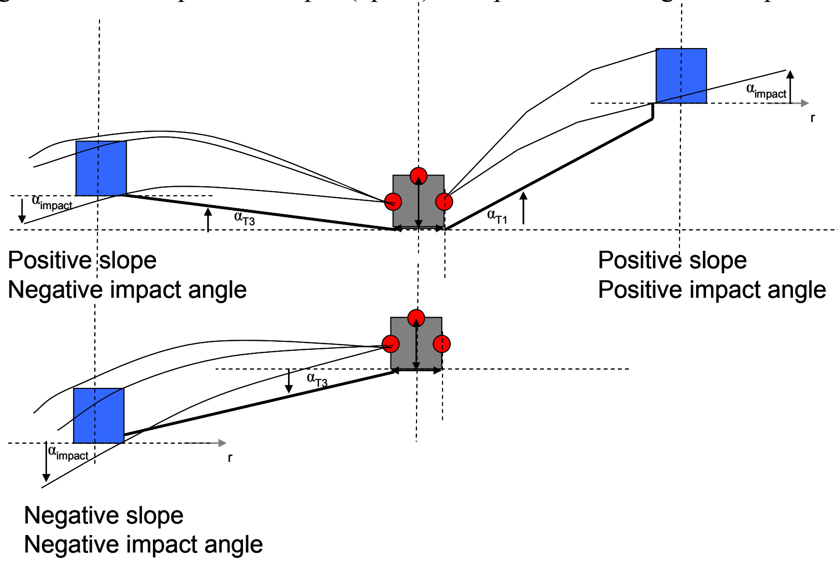

Figure 4. ***The possible combinations of terrain slope and impact angle.***

Figure 5 gives an illustration of the influence of a -15, -5, 5 and 15° sloped terrain on the debris density. The results show the decreasing impact distances with increasing terrain slope.

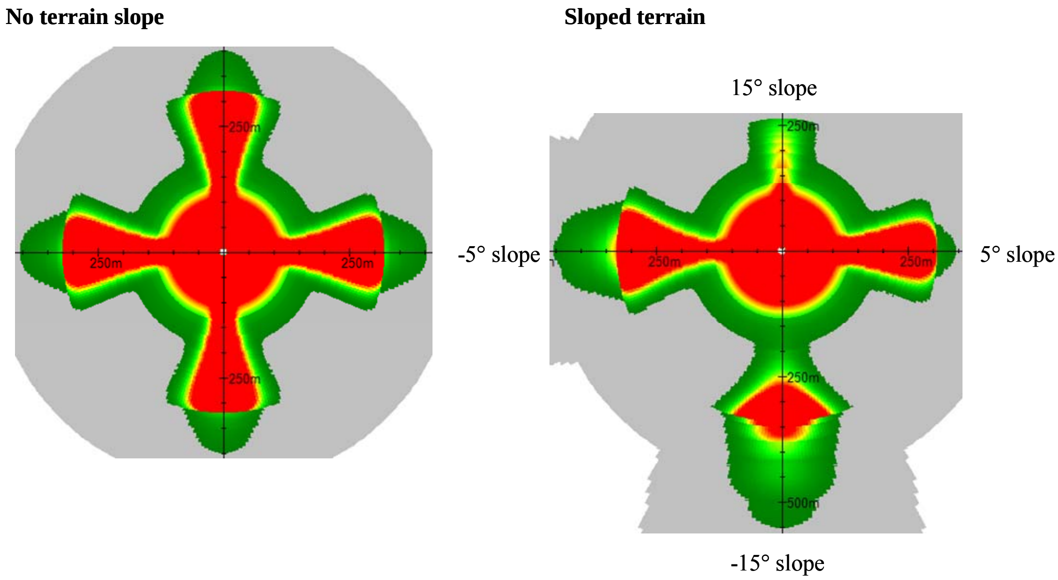

Figure 5. Illustration of the influence of a sloped terrain.

3. Barricades at PES and ES

Barricades at the PES have to be specified by setting the barricade height and its distance from the PES (Figure 2). This can be done for each of the four sides of the magazine separately. From this information the so-called ‘barricade blockage angle’ is calculated, i.e. the maximum vertical launch angle that is ‘blocked’ by the PES barricade. Barricades are assumed to be impenetrable and stationary during the explosion. Because this approach relies on the assumption of straight line trajectories, the barricade has to be specified within a certain maximum range from the PES. The exact requirements are not discussed in detail in this paper. Furthermore the relevant intervals of the azimuthal angle (in the horizontal plane) that are blocked by the barricade have to be defined. An example for realistic barricades is given in Figure 6, showing the plane of launch angles ($-90° \leq \alpha \leq 90°$) versus azimuthal angles ($0° \leq \beta \leq 360°$). The top part of the figure shows the barricade blockage angles α_{bj} and the relevant azimuthal angle intervals $\beta_{sj} \leq \beta \leq \beta_{ej}$. In the brown parts of the graph all debris is ‘blocked’ by barricades.

The bottom part of the figure gives a schematic representation of the source function for wall debris $n(\alpha, \beta)$, which represents the distribution of wall debris over azimuthal angles and launch angles. The function gives the (number) density of debris per solid angle. Within the red circles the source function has large values, i.e. a large amount of debris is thrown in these directions. The source function is centered around the wall normal directions (with the average launch angle tilted slightly upwards).

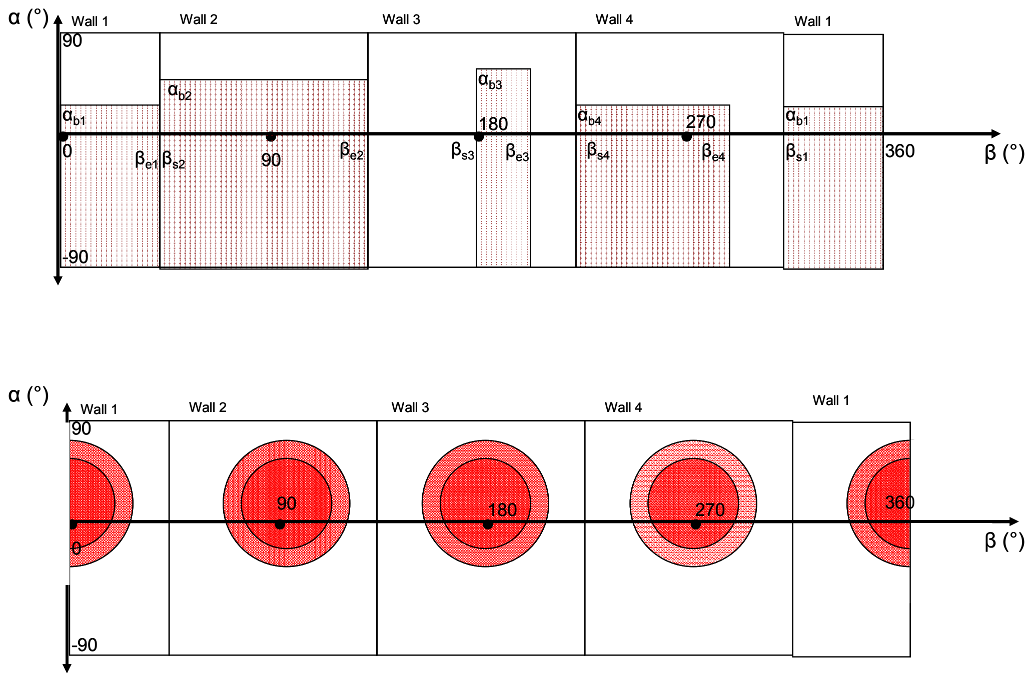

Figure 6. ***Illustration of PES barricades in the α-β plane (top). Illustration of the source function for wall debris in the α-β plane (bottom), not to scale.***

The next step in the calculation of the influence of the PES barricades, is the definition of a reduced source function $n_{red}(\alpha,\beta)$, by setting the source function $n(\alpha,\beta)$ to zero for values of α and β that are 'blocked'. Each launch angle is coupled to an impact distance by the vertical launch angle function $\alpha(r)$. This function is determined with multiple forward trajectory calculations for a variety of launch angles. The impact distances depend on the mass (bin) and velocity of the debris, and on the terrain slope discussed in Section 2. For each mass bin debris launched just over the barricade (blockage angle) is coupled to an impact distance. Below these distances no debris will impact, hence 'islands of debris' are generated above these distances. If the barricade blockage angles are large enough virtually all debris will be blocked.

The reduced source function directly leads to a reduced debris density field, using the source function theorem (Van der Voort, 2008-1 & 2008-2):

$$\Phi_{red}(r,\beta) = \frac{n_{red}(\alpha(r),\beta)\cdot\cos\alpha(r)}{r}\cdot\frac{\partial\alpha}{\partial r} \qquad (2)$$

The source function theorem is illustrated in Figure 7. It can be derived by considering an infinitesimally small surface element $\cos\alpha\cdot d\alpha\cdot d\beta$ on the unit sphere of launch angles and azimuthal angles. This element is connected by debris trajectories to a corresponding surface element $r\cdot dr\cdot d\beta$ in the horizontal plane. Through both surface elements an equal number of debris is propagating $n(\alpha,\beta)\cdot\cos\alpha\cdot d\alpha\cdot d\beta = \Phi(r,\beta)\cdot r\cdot d\beta\cdot dr$ which leads to Equation (2) for infinitesimal elements. The derivation shows that infinitesimal surface elements at launch are assumed to be linked uniquely to surface elements at impact. This holds true in the most general case only if flat and high trajectories for a given mass (bin) are considered separately, since both of them can reach the same surface element in the plane. In the present case, this distinction is not necessary, since we consider each wall (and the roof) of the PES separately.

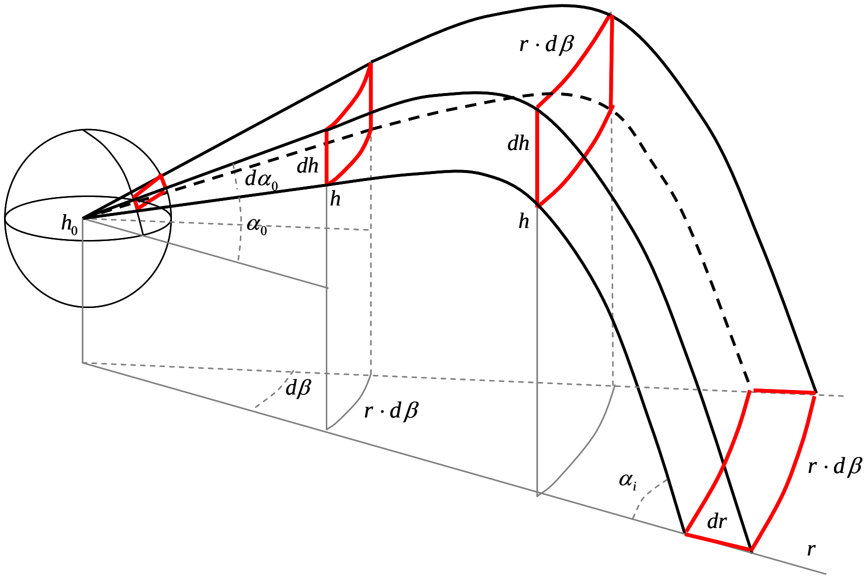

Figure 7. Illustration of the source function theorem

Figure 8 gives an illustration of the influence of a barricade blockage angle of -3, 3, 9 and 15°. The results show the formation of 'islands' of debris for increasing barricade blockage angles.

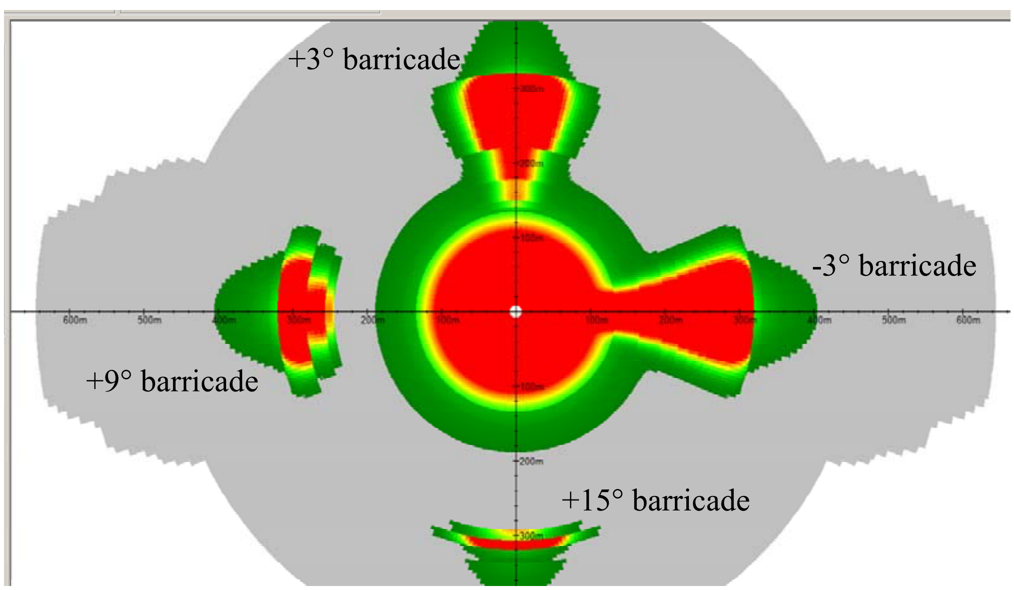

Figure 8. Illustration of the reduced debris density due to PES barricades

Barricades at the ES can be specified by a barricade height and distance from the ES, just as for the PES. However, it was decided to use rectangular barricades (Figure 2). The influence of the ES barricades is indicated in Section 4.

4. The number of hits

The ES is modeled as a rectangular box, and has to be specified by its dimensions, orientation, and barricades (Figure 2). Output is generated for two sides and the 'roof' of the ES. The ES dimensions can be chosen to match for example the human body or a building.

The number of hits at an ES can be calculated by integrating the reduced source function over the angular intervals that cover the ES.

$$N_{hitsES} = \int_{\beta_{ES\min}}^{\beta_{ES\max}} \int_{\alpha_{ES\min}}^{\alpha_{ES\max}} n_{red}(\alpha,\beta) \cdot \cos(\alpha) \cdot d\alpha \cdot d\beta \qquad (3)$$

With:

$\beta_{ES\min} \leq \beta \leq \beta_{ES\max}$ azimuthal angle interval occupied by the ES

$\alpha_{ES\min} \leq \alpha \leq \alpha_{ES\max}$ launch angle interval occupied by the ES

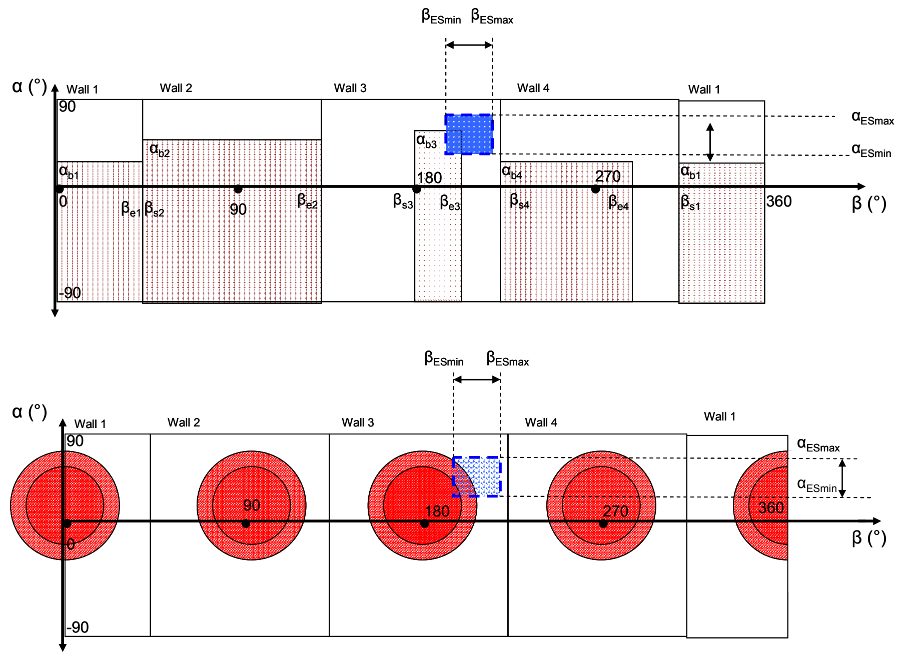

Figure 9. Illustration of PES barricades in the α-β plane (top) including angular interval of ES. Illustration of the source function for wall debris in the α-β plane (bottom) including angular interval of ES.

The angular interval of an ES component is illustrated by the blue area in Figure 9. The azimuthal angle interval is determined straightforward from the ES dimensions and the distance from PES to ES. The launch angle interval is related to the function $\alpha(r)$ which was introduced in Section 3. Because some ES components extend over the height (z) this function has to be extended to $\alpha(r,z)$. A distinction is made between the close-in regime and the far field regime for the computation of the launch angle.

Close-in:
In this regime the trajectories are well approximated by straight lines and the function $\alpha(r,z)$ can be derived in a straight forward manner from Figure 10. In the KG Software a PES wall is represented by a point source of debris at the centre of the wall (Figure 2). The angle $\alpha_{close-in,j}$ is the launch angle of debris propagating in a straight line from the point source towards the ES component at height z. Note that z is defined here relative to the (sloped) terrain, while it was defined relative to the ground level at the source in Figure 3.

$$\alpha_{close-in,j}(r,z) = \arctan\left(\frac{z-(h_0+h/2)+r\cdot\tan(\alpha_{Tj})}{r}\right) \quad (4)$$

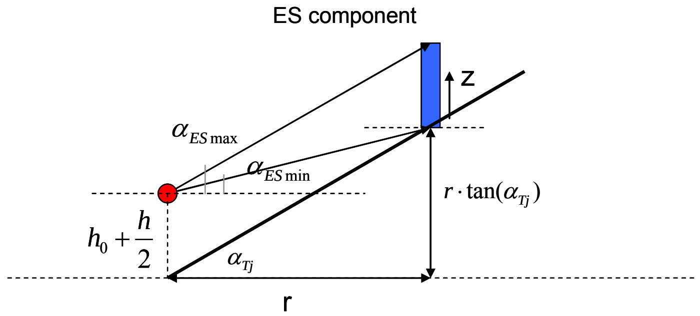

Figure 10. ***Close-in regime for debris launched from a debris source at a height $h_0 + h/2$. h_0 is the magazine elevation; h is the magazine heigth.***

Far field:
The far field trajectories can not be approximated with straight lines. To allow for fast computations only $\alpha(r)$ at z = 0 is stored, while $\alpha(r,z)$ is estimated with a Taylor expansion around z = 0:

$$\alpha(r,z) = \alpha(r) + z\cdot\frac{\partial\alpha(r)}{\partial z} \quad (5)$$

The derivative in equation (5) is estimated with the following algorithm (Figure 11)

- Perform forward trajectory calculations for impact locations behind the ES
- Register for each impact location also the impact angle
- Backward calculate height h* of the trajectory at the ES center using a straight line approximation
- If h* exceeds the ES height stop the procedure
- Then estimate the derivative as follows:

$$\frac{\partial\alpha(R_{ES})}{\partial z} \approx \frac{\alpha(R^*)-\alpha(R_{ES})}{h^*} \quad (6)$$

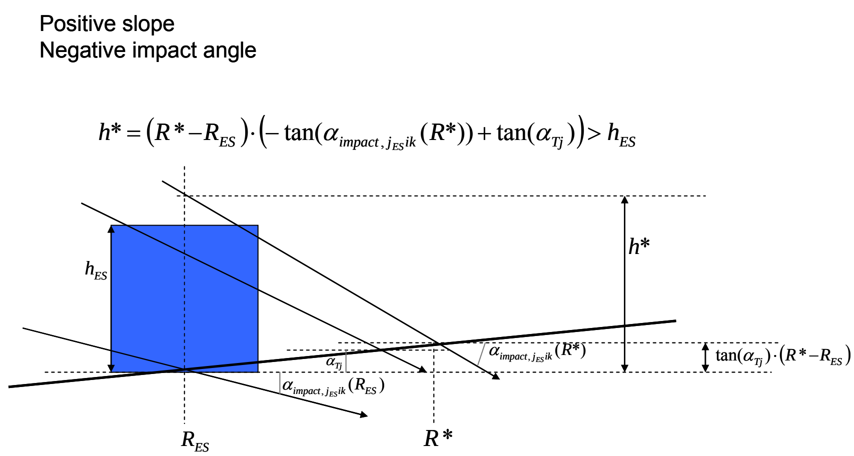

Figure 11. ***Algorithm for estimation of the launch angle interval in the far field regime.***

With the azimuthal angle and the launch angle intervals known, the integral (Equation 3) can be evaluated by discretization of the source function. In summary, this section showed how the number of hits at the wall and the roof of the ES can be computed. We did however not yet consider barricades at the ES.

The same methodology used to compute the launch angle interval for debris that hits an ES component can be used to determine the debris that hits a barricade at the ES. In this way blocking angles resulting from a barricade at the ES can be computed. These blocking angles are then added to the reduced source function which already takes into account the barricades at the PES. This leads to a new reduced source function which takes both the barricades of PES and ES into account.

5. Ballistic Filtering

Conventional models describing the flight of debris are based on the assumption of individual debris motion. However, the debris cloud originating from a reinforced concrete wall is initially very dense. As a result debris trajectories can not be considered independently at these stages. Comparing conventional models with experimental (pick-up) data has shown that small debris requires unrealistic high launch velocities to reach the observed impact distances. An example is given in Figure 12 for the Kasun II trial with 80 kg PETN in a 8 m^3 cubicle RC structure. The KG Software predicts launch velocities for mass bin 10 that are much larger than what is considered realistic (for example the characteristic velocity DLV = 121 m/s). The excess depends on the chosen type of representative mass (either maximum, middle or average). The largest excess values are found for the average mass (which is the smallest representative mass).

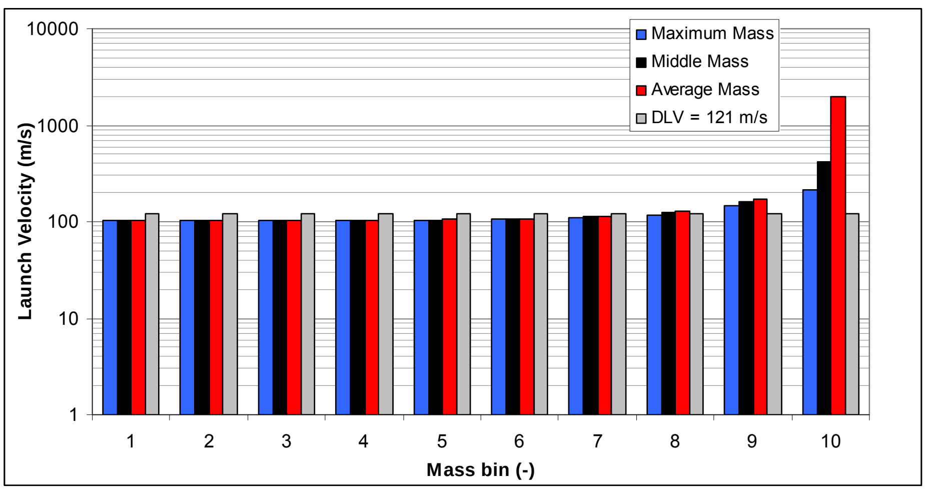

Figure 12. Launch velocity predicted with KG Software v1.0 for the 80 kg Kasun II trial, for mass bins represented by their maximum, middle or average mass.

The developed 'ballistic filtering' model gives a more realistic description of the initial stages of debris throw. It models the transition phase from an entire wall (slab) to a debris cloud and finally to individually moving debris.

The model assumes that the wall is launched with a uniform initial velocity equal to the DLV (Van Doormaal, 2006). The main parameter in the model is the so-called 'ballistic coefficient' κ, which occurs in the equations of motion, and represents the influence of drag. In general κ can be formulated as follows.

$$\kappa(M) = \frac{C_D(M) \cdot \overline{A} \cdot \rho_a}{2 \cdot m} \tag{7}$$

With:

Average presented area	$\overline{A}$	
Mass	m	(middle, maximum or average)
Density of air	ρ_a	
Drag coefficient	C_D	
Mach number	$M = v/c$	
Velocity of sound	c	

In the ballistic filtering model the ballistic coefficient of the debris cloud is initially equal to that of an intact wall, which can be written as:

$$\kappa_{wall} = \frac{C_{Dwall} \cdot \rho_a}{2 \cdot \rho_c \cdot d_{wall}}, \qquad (8)$$

since $\overline{A} = H \cdot W$ and $m = \overline{A} \cdot \rho_c \cdot d_{wall}$

where:

Thickness of wall	d_{wall}
Density of concrete	ρ_c

Figure 13 gives an illustration of the expansion of a wall to a debris cloud with an expansion angle σ_d. For zero expansion angle the ballistic coefficient of the wall would not change.

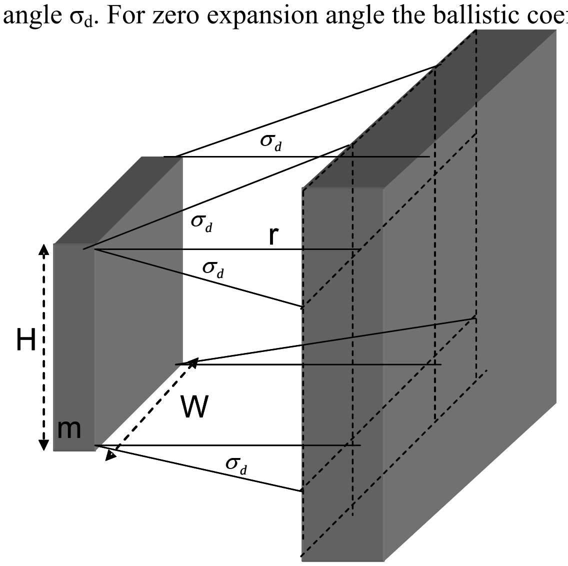

Figure 13. ***Wall (left) and debris cloud (right).***

For a finite expansion angle, the area to mass ratio of the debris cloud increases with distance r, which results in the following model for the ballistic coefficient (using the geometry at r = 0 and r):

$$\kappa_{cloud}(r) = \kappa_{wall} \cdot \left(1 + 2 \cdot \tan(\sigma_d) \cdot \left(\frac{1}{W} + \frac{1}{H}\right) \cdot r + 4 \cdot (\tan(\sigma_d))^2 \cdot \frac{r^2}{H \cdot W}\right) \qquad (9)$$

By a comparison with experimental data it was concluded that the optimal value for σ_d is close to 1.5°. At a certain distance the ballistic coefficient of the cloud will exceed the ballistic coefficient of the individual debris. This will start at the larger mass bins and continue towards the smaller mass bins. The ballistic coefficient of the debris is parameterized using the shape number:

$$\kappa_{debris} = \frac{S_n \cdot C_D \cdot \rho_a}{2 \cdot \rho_c^{2/3} \cdot m^{1/3}} \tag{10}$$

$$S_n = \overline{A}\left(\frac{\rho_c}{m}\right)^{2/3} \tag{11}$$

With:

Shape number	S_n
Drag coefficient	C_D
Density of air	ρ_a

The drag coefficient is in general a function of the Mach number. Figure 14 shows empirical models for three different shapes. The dimensionless shape number and drag coefficient model have been chosen based on a literature review and on optimization to experimental data. This is not further elaborated in this paper. It was concluded that the assumption of rotating cubes having a shape number of 1.5 in combination with the drag coefficient for a cube is the best option.

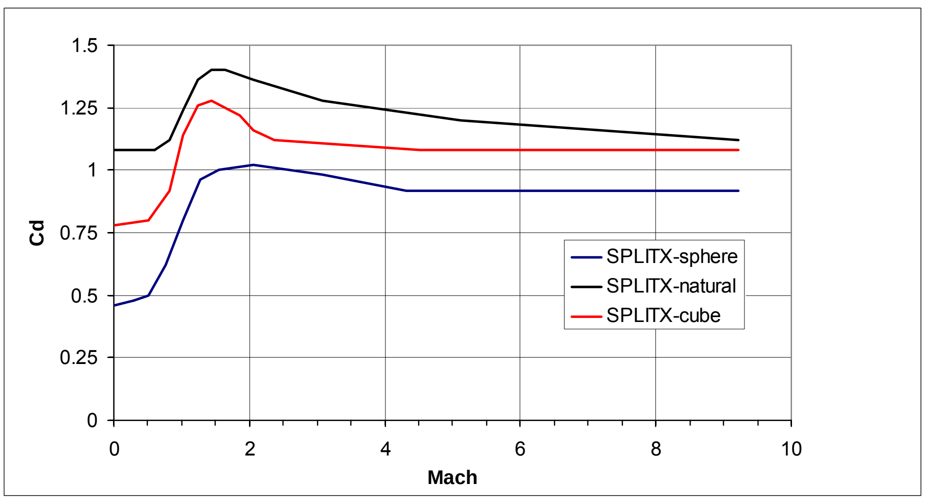

Figure 14. Drag coefficient for spheres, natural fragments and cubes as a function of the Mach number.

When the ballistic coefficient of the debris cloud exceeds that of individual debris, the debris will start to exit the cloud at the front, and move individually. The ballistic filtering model has been implemented in a research version of the KG Software. A comparison with KG Software v1.0 is shown in Figures 15 and 16. The simulations are carried out for the Sci Pan 1 trial which concerned the detonation of a bare charge of about 12 tonnes in a reinforced concrete structure with dimensions of about 10 by 10 by 5 m.

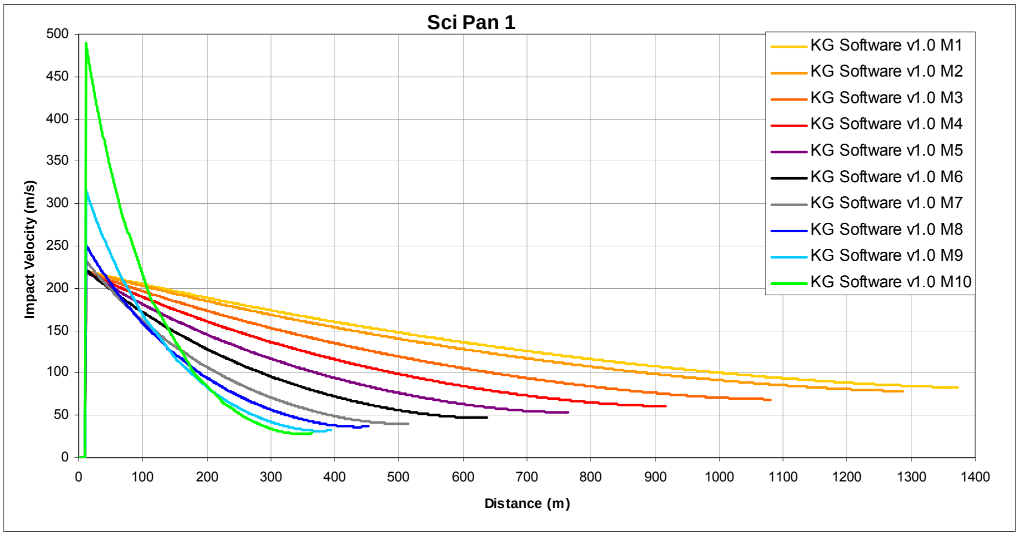

Figure 15. Impact velocity versus distance calculated with the KG Software v1.0.

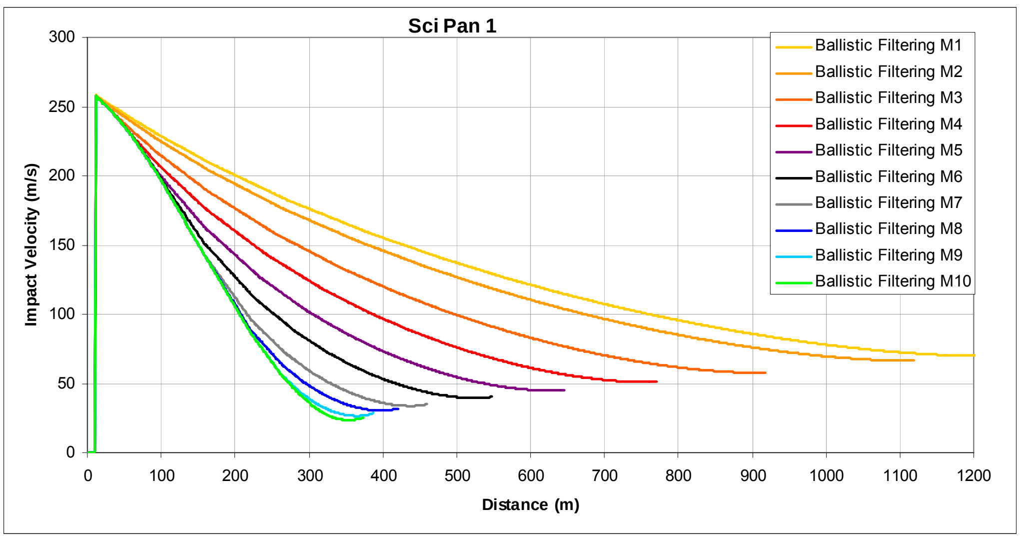

Figure 16. Impact velocity versus distance calculated with the research version for $S_n = 1.5$, drag coefficient for cubical shape, and $\sigma_d = 1.5°$.

Figure 15 shows the impact velocity of debris versus distance, predicted with KG Software v1.0. Note the (unrealistic) high impact velocities for the small masses (mass bins 9 and 10). Figure 16 shows the more realistic behavior of a wall/debris cloud that is launched as a whole with the DLV and propagates according to the ballistic filtering model. At launch the impact velocities are equal as intended by the modeling. Initially also the decay rate of the velocity is equal for all mass bins. Then starting with the larger mass bins a smooth transition takes place between collective and individual motion of the debris.

Figure 17 shows a comparison in terms of the debris density. Although the trajectory description has significantly changed, the differences in the debris density are only minor.

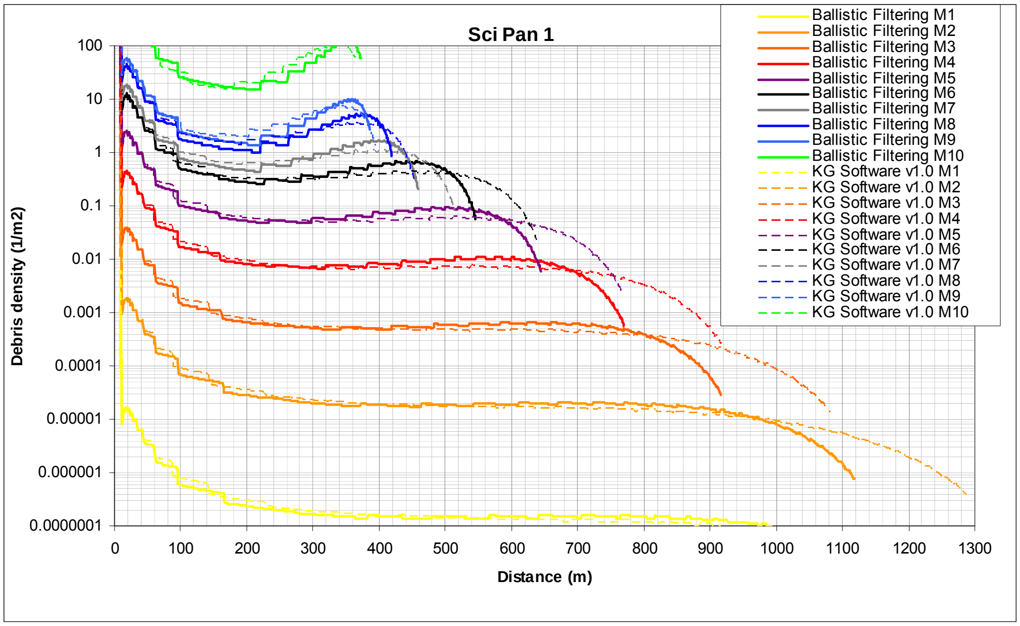

Figure 17. ***Debris density versus distance calculated with KG Software v1.0, and with the research version for $S_n = 1.5$, drag coefficient for cubical shape, and $\sigma_d = 1.5°$***

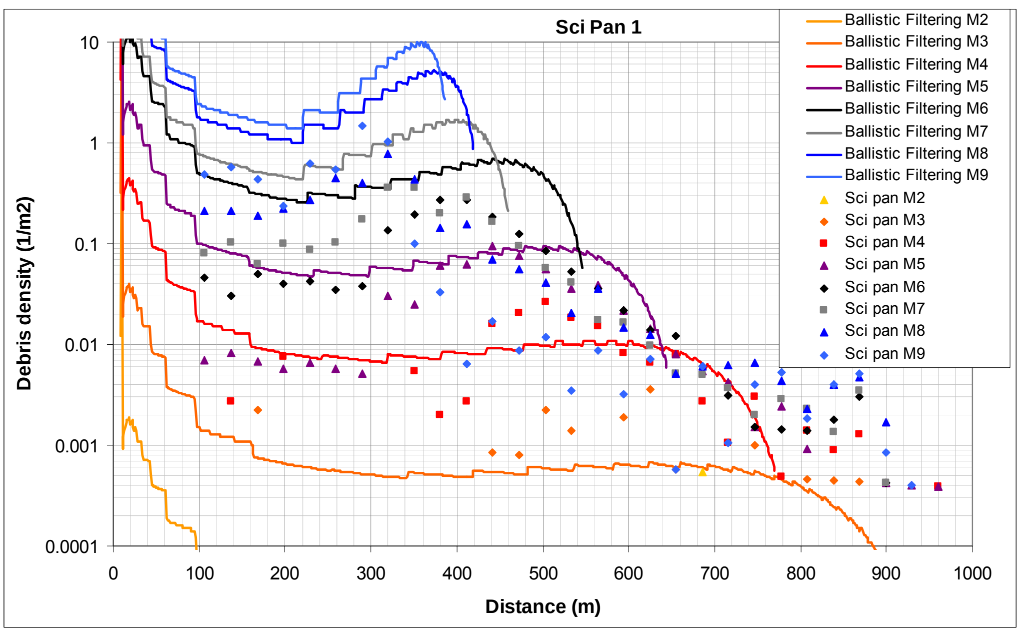

Figure 18. ***Debris density versus distance calculated with the research version for $S_n = 1.5$, drag coefficient for cubical shape, and $\sigma_d = 1.5°$. Experimental results are also shown.***

Figure 18 compares the calculation results from the ballistic filtering model to experiments. The resemblance with the experimental data is of a similar quality as the KG Software v1.0. However, the ballistic filtering model has the following advantages over the current modeling in KG Software v1.0:

- More realistic prediction of trajectories, and more realistic launch and impact conditions. This is especially relevant for the use of the KG Software as a consequence model in risk assessment.
- No more dependence on backward calculations and related launch assumptions.

- Freedom to vary and optimize the above mentioned parameters to experimental data.

A decision whether the ballistic filtering model should be included in a new version of the KG Software will be taken at the KG Fall meeting 2010.

6. Conclusions

An overview has been given of recent developments of the KG Software.

A number of these new features is related to risk assessment application. The first one is the possibility to define a sloped terrain, to enhance the applicability of the software in various countries. Furthermore the possibility to calculate the number of hits at user-defined exposed sites, and the possibility to specify barricades at the PES have been added. It has been discussed how barriers at the PES can be taken into account. The new features have been implemented in a joint project by TNO and EMI.

In addition to these new features, the paper also addresses the improvement of the debris trajectory prediction. Conventional models describing the flight of debris are based on the assumption of individual debris motion at launch. However, the debris cloud originating from a reinforced concrete wall is initially very dense. As a result debris trajectories can not be considered independently at these stages. Comparing conventional models with experimental data has shown that small debris requires unrealistic high launch velocities. The developed 'ballistic filtering' model gives a more realistic description of the initial stages of debris throw. The model has been implemented in a research version of the KG Software and has been compared to trial data, showing good correlation.

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