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Simple methods of estimating the hazardous area for a multiple blast situation

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English summary

Active Protection Systems (APS) may cause injury to personnel nearby. To estimate the potential injury from an APS we examine the general case of two charges detonating in relative proximity. Three different methods for estimating the combined hazardous areas and corresponding distances are evaluated by comparing with results from numerical simulations using ANSYS AUTODYN.

Sammendrag

Aktive beskyttelsessystemer (APS) kan forårsake uønsket skade på personell i nærheten. For å estimere potensiell skade fra et APS ser vi på det generelle tilfellet hvor to ladninger detonerer i nærheten av hverandre. Tre forskjellige metoder for å estimere skadelig areal og avstand undersøkes og sammenlignes med resultater fra numeriske simuleringer i ANSYS AUTODYN.

Contents

1 Introduction

Active protection systems[1] (APS) are typically mounted onto military vehicles for protection against shape charged missiles and rockets such as RPG and similar [1,2]. APS contain countermeasures (CM) which tend to render the incoming threat harmless (or degraded) to the object under protection. The CM is either activated close to the vehicle ("close-in systems"), or launched towards the incoming threat and activated at some distance from the vehicle ("launcher-based systems").

The activation of the CM is very often based on an explosive charge. As the threat most likely contains explosives, it may also detonate as a result of the interception from the CM. In any case, the blast waves originating from the explosions are potentially harmful to personnel and may (unintentionally) inflict collateral damage on the surroundings when the CMs intercept incoming threats.

For safety reasons it is obviously of great importance to know the potential collateral damage (CD) caused by the explosions. One source of CD is blast overpressure, others include e.g. fragments, heat, and toxicity. Here we address only blast. It is useful to define the term hazardous zone. This is understood as an area where the blast overpressure (or other injury parameter) is above a critical level according to a given injury criterion.

Live testing of an APS event will result in non-static blast sources (launched CM and incoming threat, both typically travelling with velocities at about a few hundred meters per second), resulting in a diffuse interception point. This challenges the measurement team upon deciding the position of the blast sensors prior to the rather expensive tests. With a simple procedure for estimating the hazardous zone, many difficulties can be avoided. It should be noted that the incoming threat does not necessarily detonate; it may be intercepted without having any reaction at all, or it could be disposed in a low order explosion (deflagration). It all depends on the mode of operation of the APS. This report, however, is based on the most severe situation possible, which is both CM and threat detonating, and which should be the point of departure in designing the test setup.

There exist numerous criteria for estimating the injury from a given explosion, see for instance [3-7]. In this report we are not interested in the criteria themselves, but instead our objective is to find a simple (approximate) way of estimating the combined hazardous zone produced by two simultaneous explosions.

In the following chapters we will explore three simple approximate procedures and compare their results with the "true" hazardous zone calculated using numerical simulations with ANSYS AUTODYN.

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[1] Also: Defensive Aid Suites (DAS)

2 Approximate procedures

In order to avoid problems with diffuse interception points and multiple blast sources, the suggested simplified test procedures are based on individual static testing or calculations of the countermeasure and incoming threat respectively. Since these procedures are applicable also for other situations than testing APS, we will use "Charge 1" and "Charge 2" instead of "CM" and "Threat".

The masses (m_1 and m_2) and/or the corresponding hazardous distances (r_1 and r_2) for the two charges (Charge 1 and Charge 2), and the typical distance between the two sources when detonating (d), are used to estimate the combined hazardous zone.

In total, three different methods are suggested below. The flow chart in Figure 2.1 gives an overview of the three approximations and the parameters used in calculating each of them.

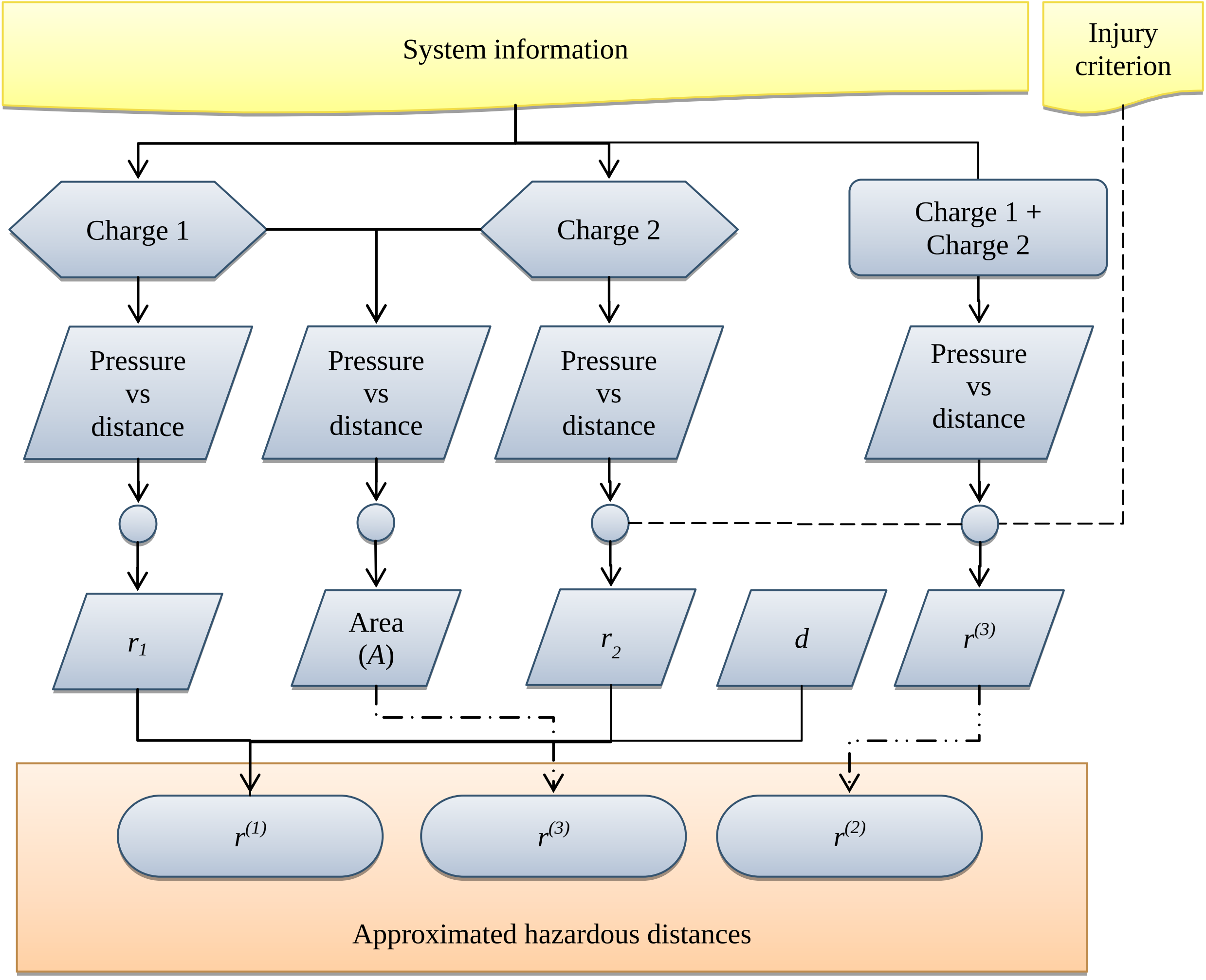

Figure 2.1 Flow chart showing the link between the parameters and the various approximations to estimate the hazardous zone.

2.1 Approximation 1

The first approximation is schematically shown in Figure 2.2. The hazardous radius of Charge 1 and Charge 2 is found by individual static testing, and drawn as two circles with the origin a distance *d* from each other. The combined hazardous zone is the (red) circle which envelope both the individual circles. In mathematical terms, this could be expressed as:

$$\begin{aligned} r^{(1)} &= \frac{r_1 + d + r_2}{2} && ;\min(r_1, r_2) + d > \max\,(r_1, r_2) \\ r^{(1)} &= \max(r_1, r_2) && ;\text{ otherwise} \end{aligned} \qquad (2.1)$$

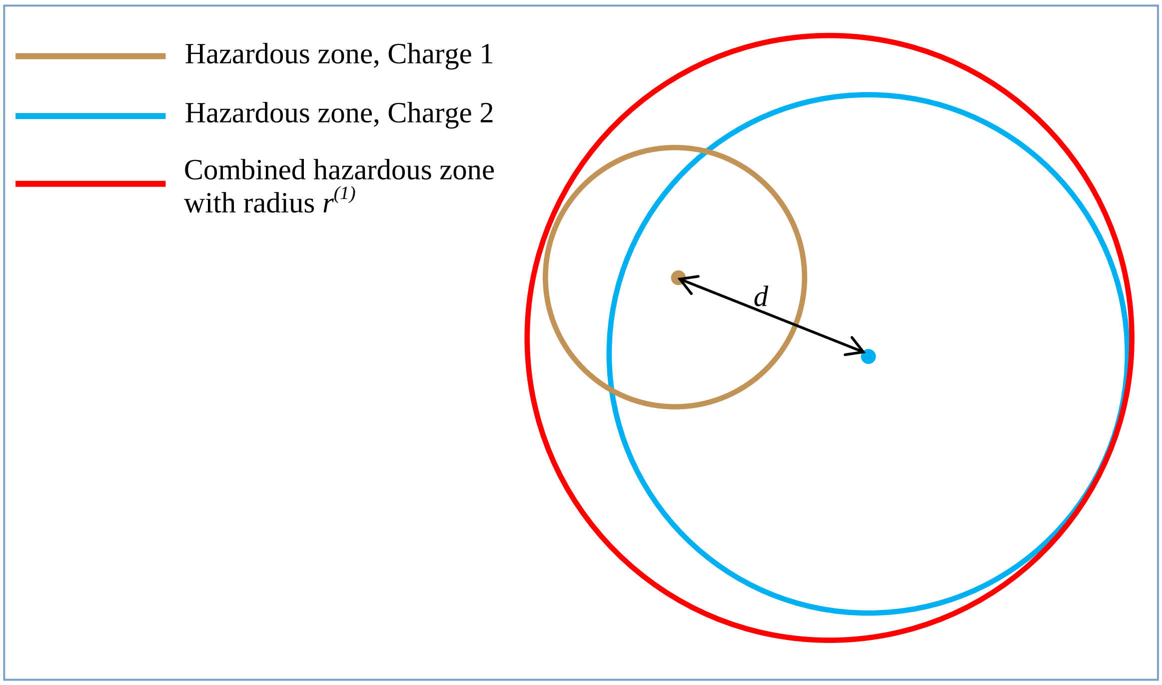

Figure 2.2 Schematically description of Approximation 1 and how to finding the combined hazardous zone.

2.2 Approximation 2

This second approximation is based on treating the two charges as one, positioned in the centre of mass (CoM), and with a mass equal to the sum of the two charges. The combined hazardous circular zone, with radius $r^{(2)}$, is then determined by assessing the blast pressure originating from the total charge.

2.3 Approximation 3

This procedure estimates the hazardous zone, with radius $r^{(3)}$, by transforming the area of the "true" (simulated) hazardous zone (*A*) into a circle with its origin in the CoM. Hence:

$$r^{(3)} = \sqrt{\frac{A}{\pi}} \qquad (2.2)$$

3 Numerical simulations

To test the approximate procedures outlined in Chapter 2, numerical simulations were performed. First we describe the scenarios used to evaluate the methods, then how the simulations were set up.

3.1 Test scenarios

Test scenarios (Table 3.1) were set up varying the masses of the two charges (m_1 and m_2) and the typical distance (d) between them upon detonation. The selected scenarios aim to span the typical situations expected to be found for launcher-based APS systems, where this problem is deemed more severe than for close-in systems.

Table 3.1 Test matrix.

Scenario	m_1 *(kg)*	m_2 *(kg)*	d *(m)*
1	0.250	0.250	0.5
2	0.250	0.250	2.0
3	5.0	0.250	0.5
4	5.0	0.250	2.0
5	5.0	2.0	0.5
6	5.0	2.0	2.0

The idea was to compare the estimates of the three methods with the “true” shape of hazardous zone found from the numerical simulations. For convenience, a simple injury criterion with a critical level of 35 kPa peak overpressure was used. This corresponds to a 50 % chance of eardrum rupture [7]. As explained earlier, the choice of injury criterion is not of prime importance, but the selected choice is realistic and reasonable.

In the scenarios we assume free field conditions, i.e. there are no reflecting surfaces anywhere. In a real APS situation, the threat and CM may detonate relatively close to the ground which will lead to reflections and potentially an increase in the hazardous zone. However, for launcher-based systems the detonations take place higher up in the air compared to close-in systems.

3.2 Simulation setup

Simulations of all the scenarios were performed using the Euler Multimaterial processor in ANSYS AUTODYN 13.0. The simulations were in general run in two stages. As long as the situation remained spherically symmetric, a 1D wedge simulation was used with a grid resolution of 1 mm. In the second stage, the final states of the 1D simulations were remapped into a 2D grid with axial symmetry and run to completion. The 2D grid had cell sizes of 20 mm x 20 mm.

Scenarios 1 and 2 where the two charges had the same mass, is equivalent to one charge near an infinitely hard wall and this was exploited to reduce the grid size and computation time. In the other scenarios, the 1D-simulation was first run for the 5 kg charge (the largest) until the blast wave had propagated a distance equal to half the distance (*d*/2) between the two charges. The 1D simulation, for the second chage, was then run for an equal amount of time and both results were remapped into the 2D grid for the final computation. (Since the blast wave of the smaller charge propagates slightly slower than for the 5 kg charge, it would have been possible to run the 1D-simulations slightly longer before remapping to 2D, but for simplicity this was not done.)

Material models from the AUTODYN material library were used. The explosive was modelled using the JWL-model and air was modelled using the ideal gas EOS.

A user subroutine, originally made for calculations of results from the Axelsson human injury model, was used to record the maximum pressure in a given cell during the propagation of the blast wave (this is not a variable in standard AUTODYN). This could be used for plotting the injury contour. For maximum flexibility, the grid data were exported to a text file and a script was written to import the data into Matlab for further processing.

In Figure 3.1 we show the propagation and interaction of the shock waves (pressure contour) from the two charges in Scenario 6. We note that the interaction is at first quite complex, but at distances further out, the resulting blast wave seems to approach a spherical form.

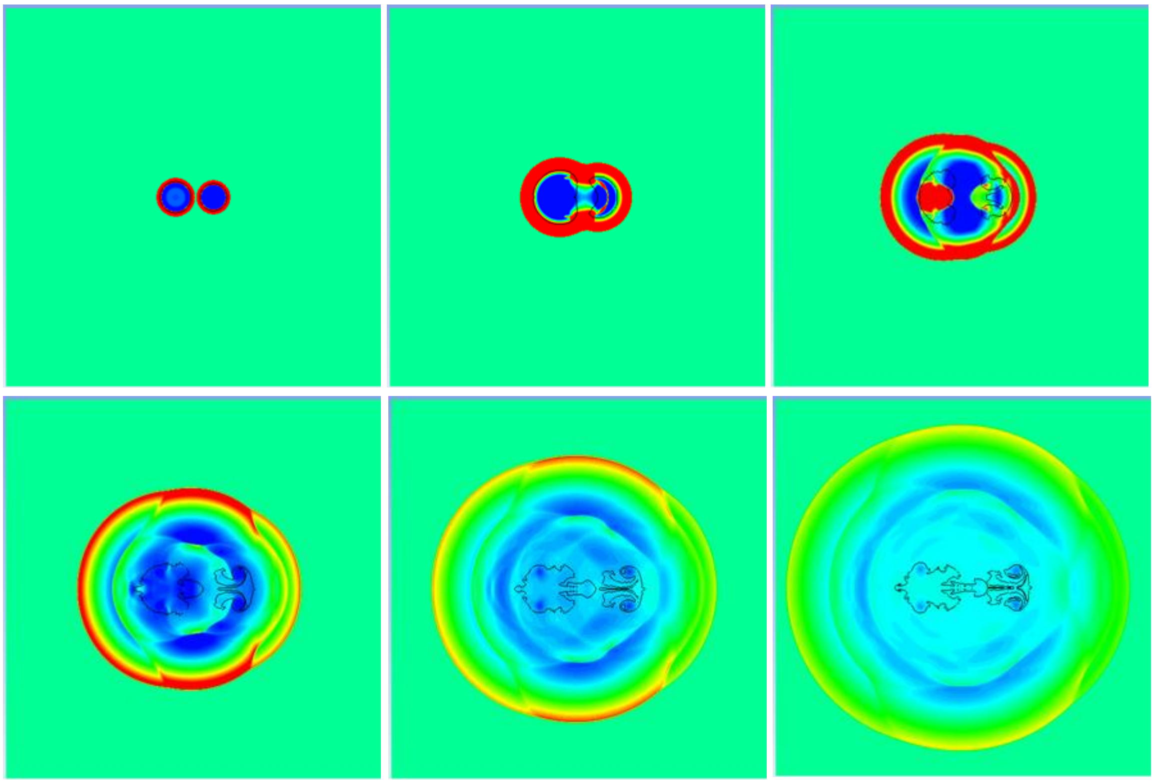

Figure 3.1 Pressure contour of propagation of the shock wave in Scenario 6.

4 Results

This section first reports the calculation of the hazardous distances for single charges, then the resulting hazardous distances found by numerical simulations of two charges detonating at the same time.

4.1 Single charges

It is necessary to know the hazardous distances for various single charges (Charge 1 and Charge 2 alone, as well as the combinations of Charge 1 and 2 in each scenario) to apply the approximate methods. These were found using standard equations for pressure versus distance [8]. Some of them were verified using AUTODYN and excellent agreement was found. Results are shown in Table 4.1 and Figure 4.1.

Table 4.1 Calculated hazardous distance for single charges using 35 kPa overpressure as the critical level.

Charge mass (kg)	*35 kPa range (m)*
0.250	2.95
0.5	3.72
2.0	5.81
5.0	7.82
5.25	8.15
7.0	8.96

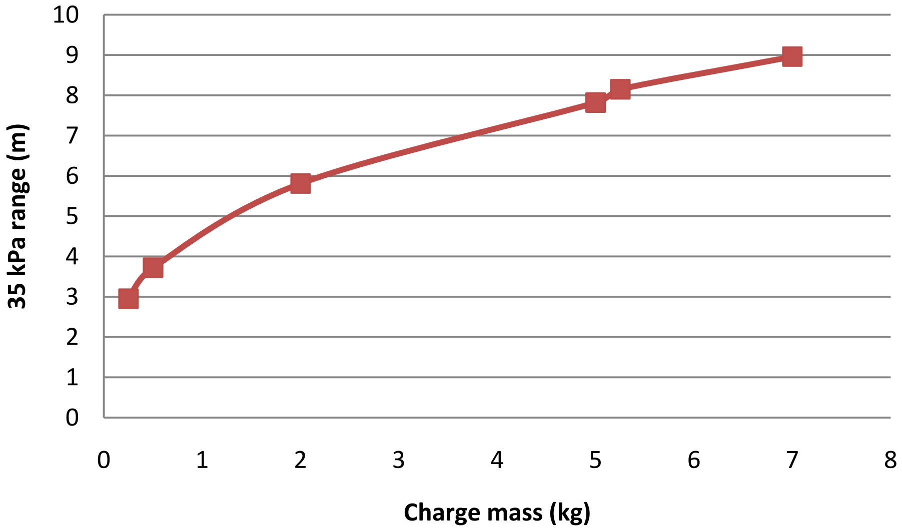

Figure 4.1 Hazardous distances as a function of charge mass for a single charge, using 35 kPa overpressure as the critical level.

4.2 Double charges

In Figures 4.2-4.7 the results from the six scenarios are shown graphically. The combined hazardous zone is compared with the hazardous circular zones found by using the three approximations described in Chapter 2. Also, the hazardous zones for the two individual charges are plotted for comparison.

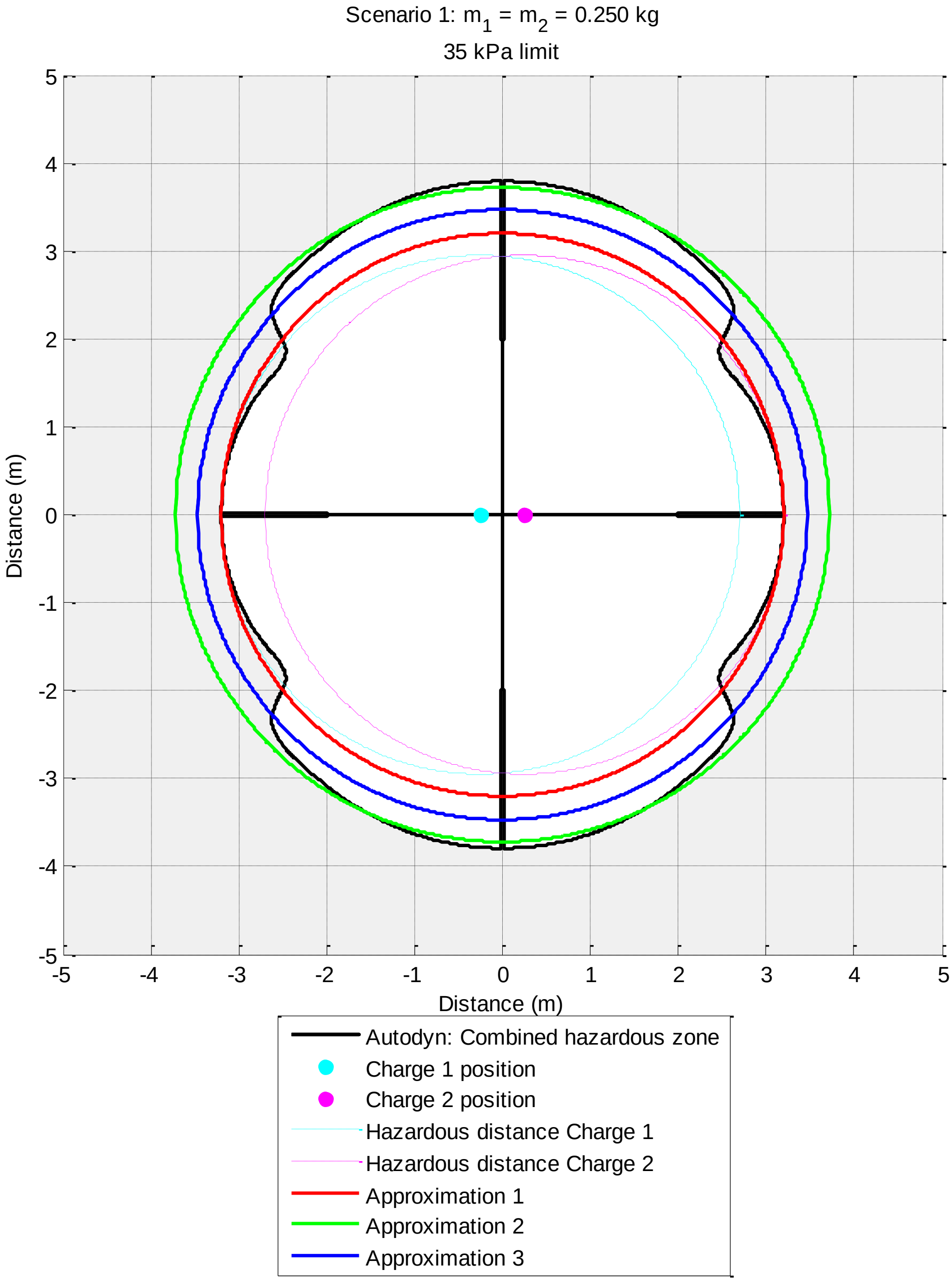

Figure 4.2 Result, Scenario 1.

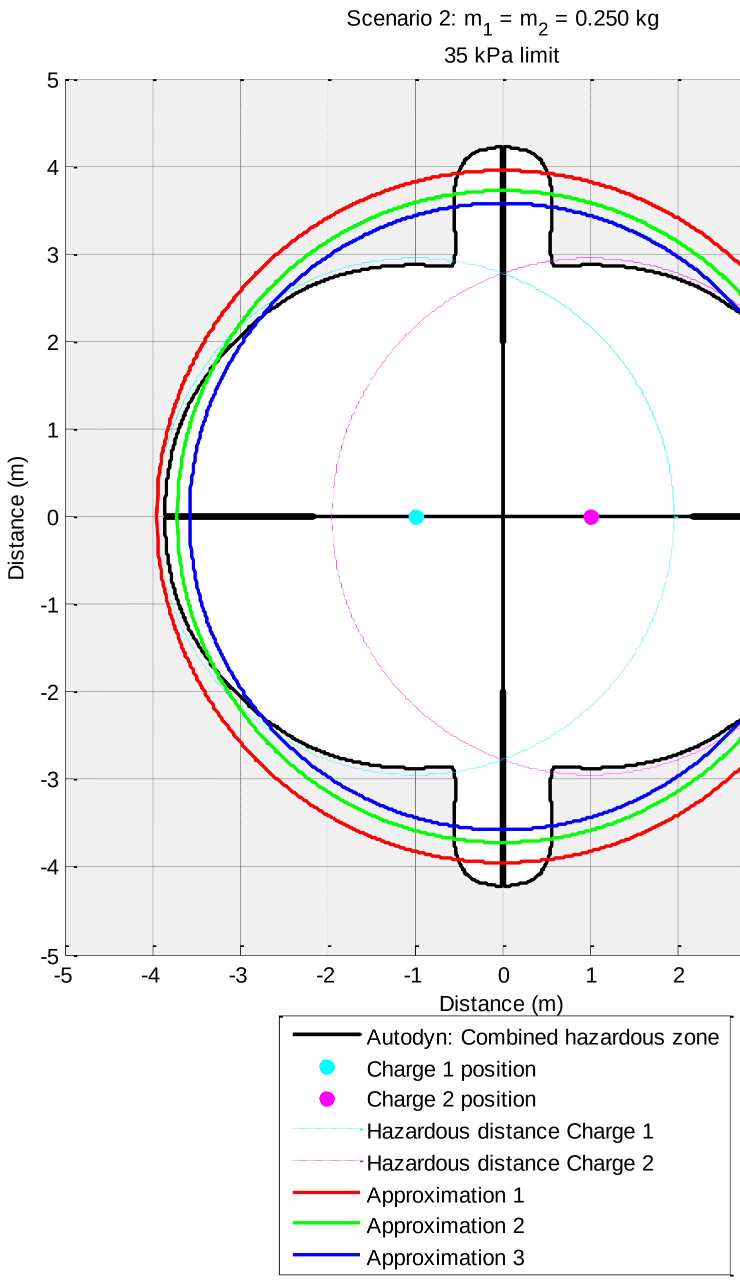

Figure 4.3 Result, Scenario 2.

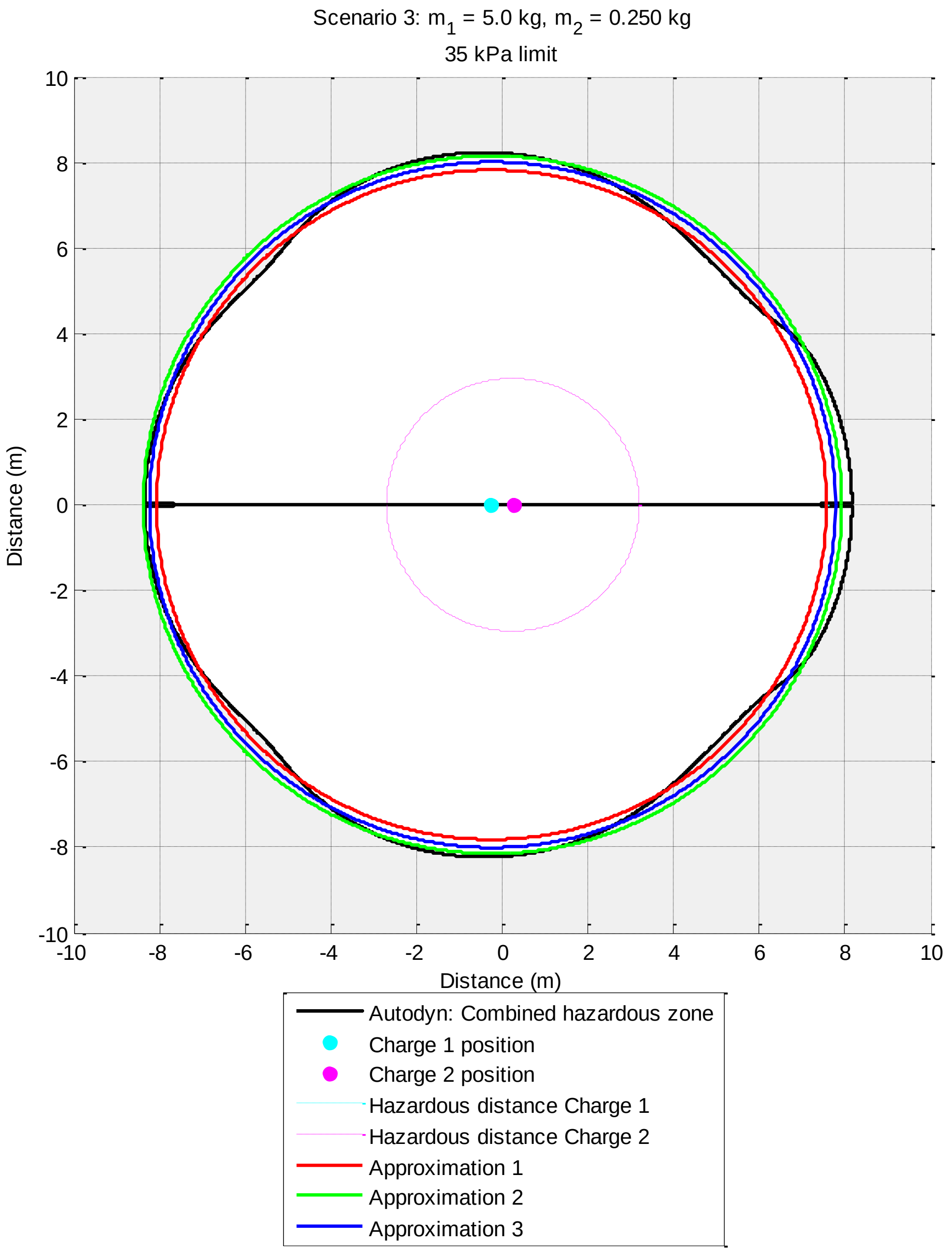

Figure 4.4 Result, Scenario 3. Curve for "hazardous distance Charge 1" is overlapped by the curve representing Approximation 1.

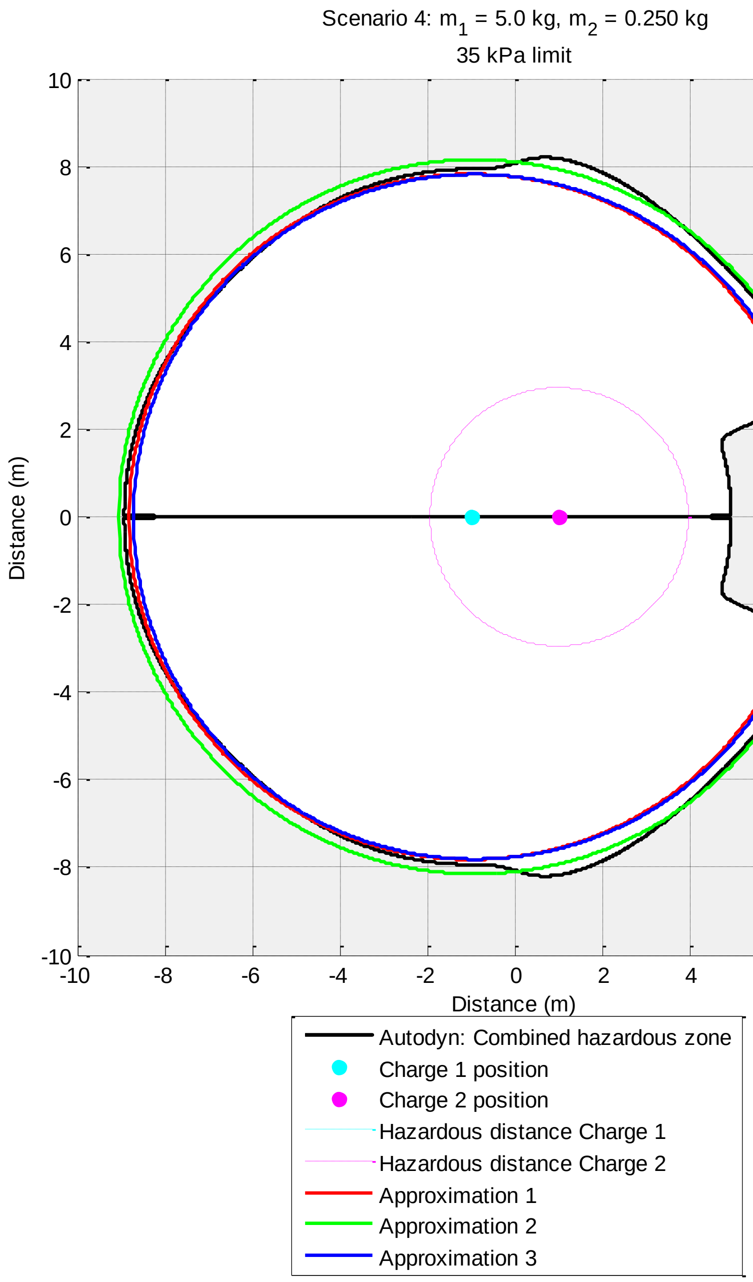

Figure 4.5 Result, Scenario 4. Curve for "hazardous distance Charge 1" is overlapped by the curve representing Approximation 1.

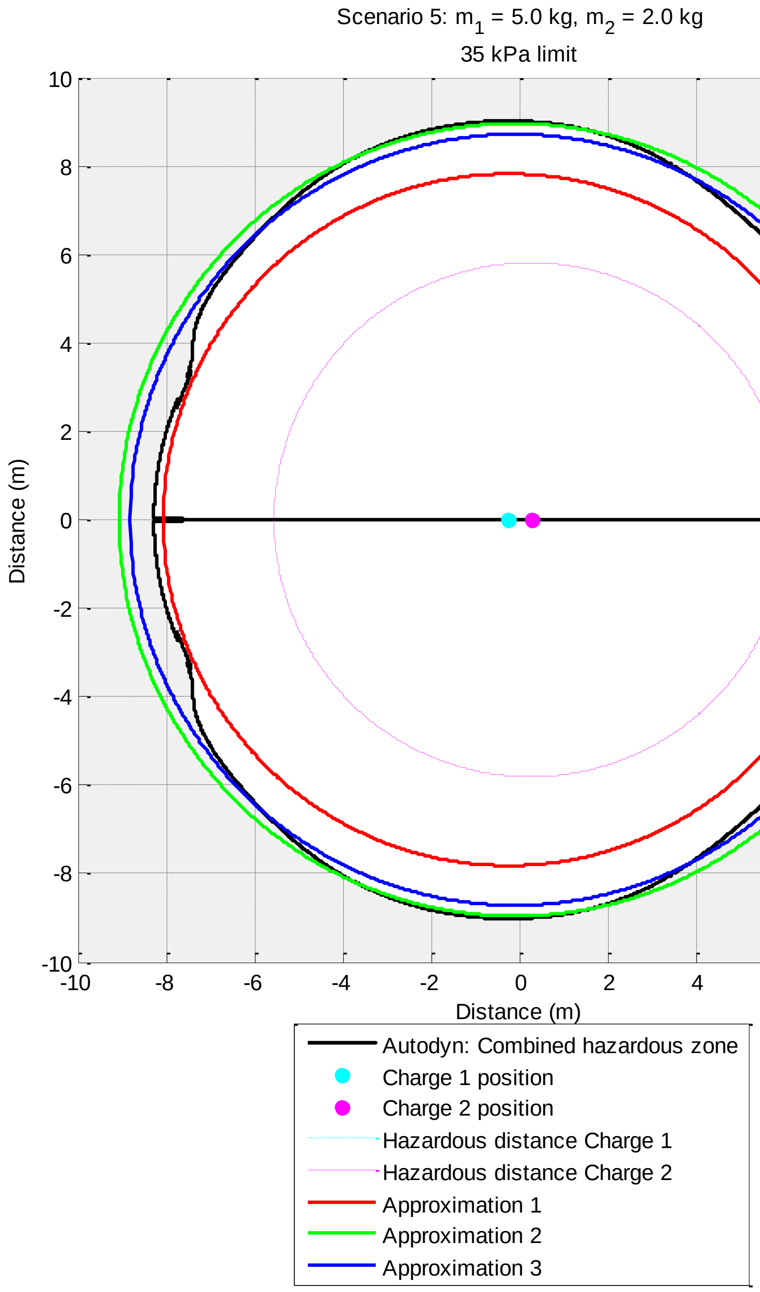

Figure 4.6 Result, Scenario 5. Curve for "hazardous distance Charge 1" is overlapped by the curve representing Approximation 1.

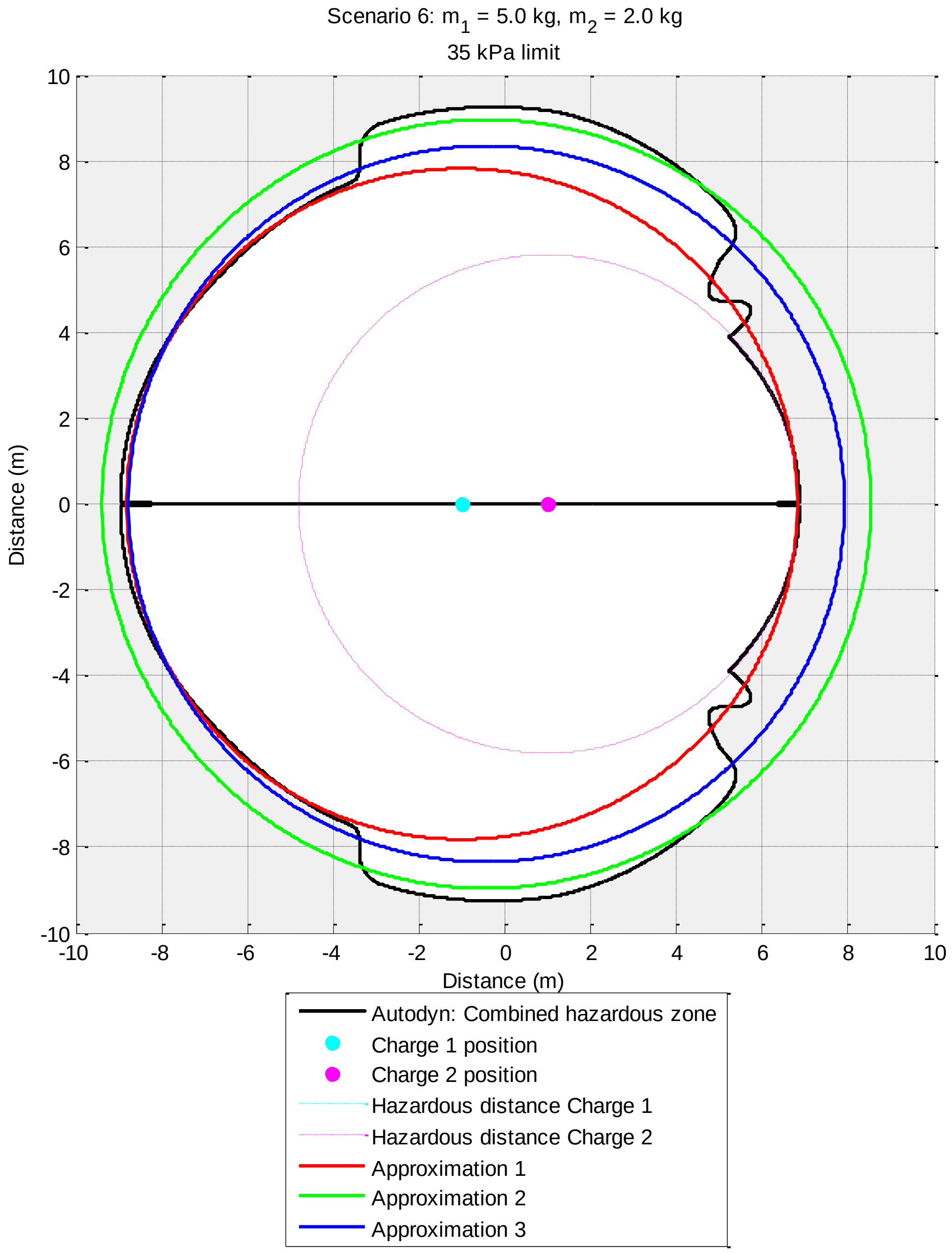

Figure 4.7 Result, Scenario 6. Curve for "hazardous distance Charge 1" is overlapped by the curve representing Approximation 1.

4.3 Discussion

The hazardous zones, when two charges detonate simultaneously at a distance *d* from each other, are in general (and as expected) not circular due to the interaction of the two blast waves. In most cases, the highest pressure levels found are either in the direction of the axis connecting the two charges, or perpendicular to it.

In the following sections, we try to quantify the accuracy of the various circular approximations to the "true" hazardous zone found by numerical simulations. One approach is to compare the area. In the example below (Figure 4.8), the area of the "true" hazardous zone that is not contained within the approximation, marked green. This area, is compared to the total area of the "true" hazardous zone, and is in this context a measure of the error of the approximation.

The approximate hazardous zone should have a radius as small as possible, but at the same time, it should contain the entire true hazardous zone. This is to be regarded as a conservative approach. Because, there will be a small area contained within the approximate hazardous zone which is not really "true" hazardous (by comparing to the simulations). The inclusion of this non-hazardous area is in this case an accepted error and thus not included in the evaluation.

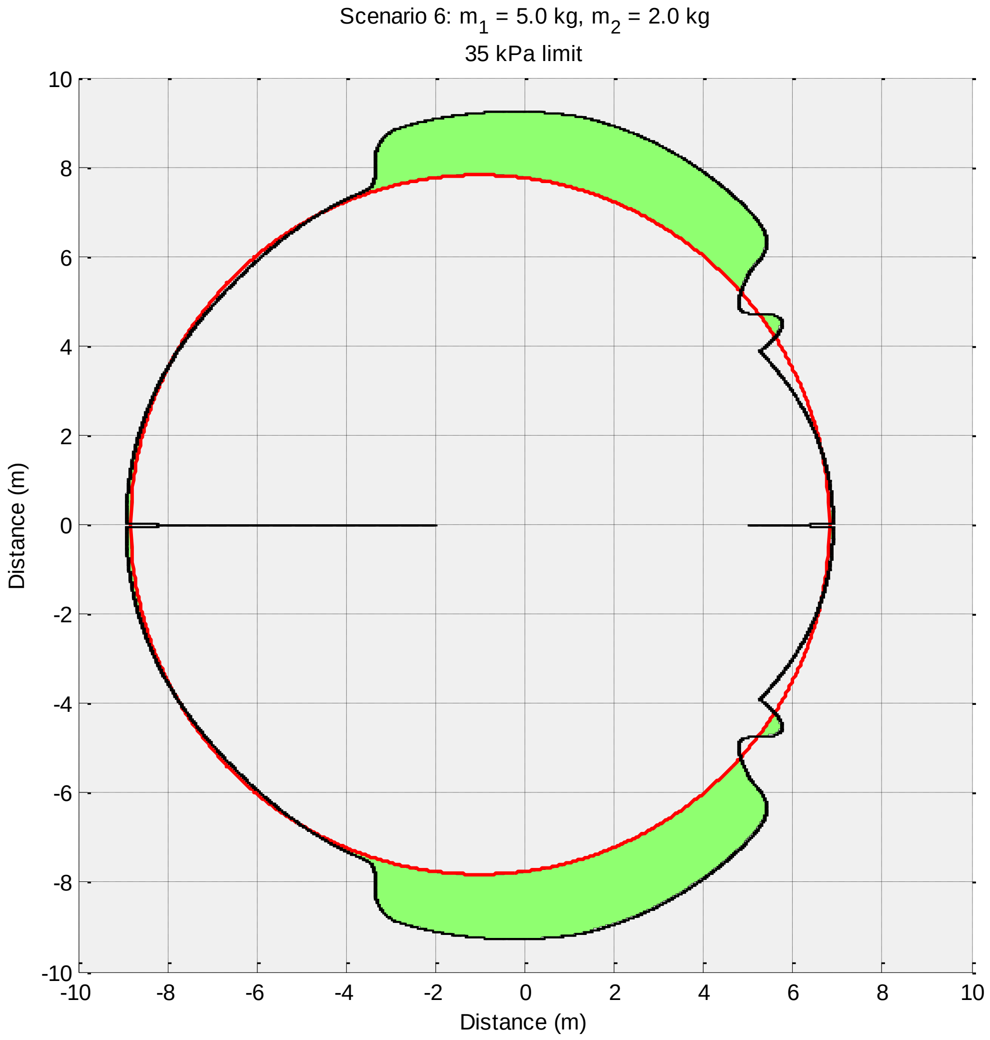

Figure 4.8 Example of true hazardous area outside the circular approximation (green). This figure is based on Scenario 6. The red line is Approximation 1.

4.3.1 Comparing the physical outputs

In Table 4.2, the area of the true hazardous zone and approximate hazardous zones are listed for each scenario. The area, which falls outside the approximate circular zone, is also given together with the error, as described above. The error is, for convenience, graphically represented in Figure 4.9.

Table 4.2 Area of the true hazardous zone, compared to the hazardous area of the three approximations. The error, that is true hazardous area outside the approximate area, is quantified both in absolute values and relative values.

Sce-nario	*Autodyn*	*Approximation 1*			*Approximation 2*			*Approximation 3*		
	True haz.area (m^2)	*Haz. area (m^2)*	*Area outside (m^2)*	*Error (%)*	*Haz. area (m^2)*	*Area outside (m^2)*	*Error (%)*	*Haz. area (m^2)*	*Area outside (m^2)*	*Error (%)*
1	37,8	32,2	6,1	16,2	43,5	0,3	0,9	37,8	3,0	7,8
2	40,2	49,0	0,4	1,0	43,5	4,0	10,0	40,2	3,2	7,9
3	201,5	192,1	11,0	5,5	208,7	1,9	0,9	201,5	5,1	2,5
4	191,8	192,1	9,0	4,7	208,7	1,2	0,6	191,8	9,3	4,9
5	238,7	192,1	46,9	19,6	252,2	2,4	1,0	238,7	7,7	3,2
6	218,8	192,1	28,5	13,0	252,2	3,9	1,8	218,8	16,2	7,4

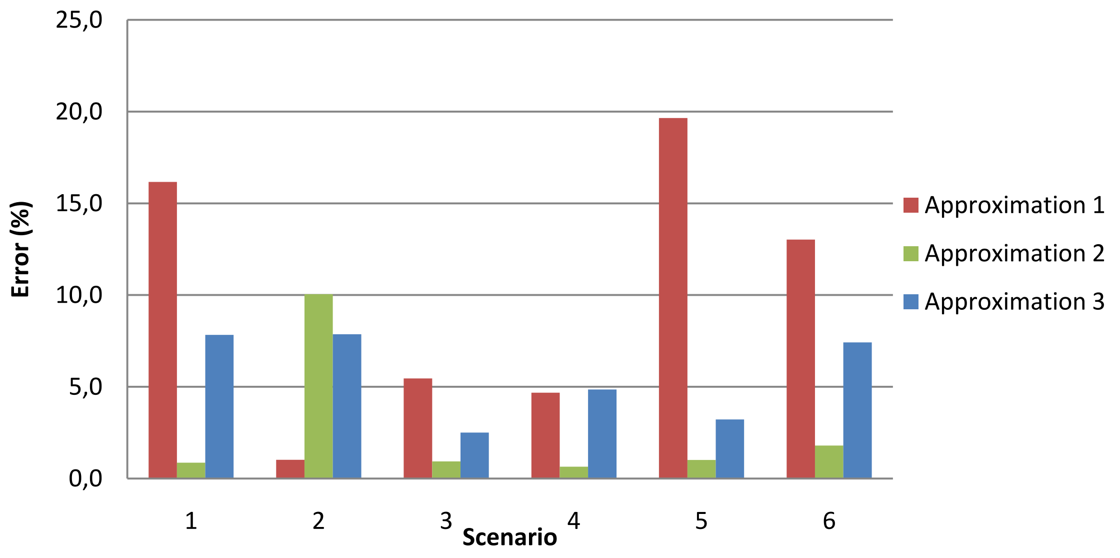

Figure 4.9 The error listed in Table 4.2.

Looking at Figure 4.9, the overall best procedure is Approximation 2. It gives errors less than 2 % except for Scenario 2 where the error is 10 %. The second best approximation would be Approximation 3 where the error is less than 8 % for all scenarios. Approximation 1 has the highest levels of errors for all scenarios, except Scenario 4 in which it is comparable to Approximation 3, and Scenario 2 where the error is only 1 %.

Table 4.3 summarizes the "true" (maximum) hazardous range found by the simulations together with the estimated hazardous range from the approximate methods described in Section 2. These numbers show the same trend as the one in Table 4.2.

Table 4.3 Hazardous range for the various approximations, and compared to the "true" (maximum) hazardous range found by simulations.

Scenario	*AUTODYN*	*Approximation 1*		*Approximation 2*		*Approximation 3*	
	True haz. range (m)	$r^{(1)}$ *(m)*	*Deviation (%)*	$r^{(2)}$ *(m)*	*Deviation (%)*	$r^{(3)}$ *(m)*	*Deviation (%)*
1	3,8	3,2	-16,2	3,7	-2,6	3,5	-9,2
2	4,3	3,9	-7,3	3,7	-12,7	3,6	-16,0
3	8,4	7,8	-6,4	8,2	-2,4	8	-4,1
4	8,5	7,8	-16,2	8,2	-4,1	7,8	-8,1
5	9,4	7,8	-17,0	9,0	-4,9	8,7	-7,5
6	9,3	7,8	-15,5	9,0	-3,1	8,3	-9,8

There are several things worth noticing. First of all is the fact that all approximations give errors (looking at the area) less than about 20 %, which is not really alarming. However none of them is able to include the entire "true" hazardous zone, hence the hazardous approximate ranges are always smaller than the (maximum) "true" hazardous range.

Looking into the details, Approximation 2 seems to work very well for all scenarios, except Scenario 2. On the other hand, Approximation 1 seems to work very well for Scenario 2, and is less accurate for the other scenarios. Scenario 2 differs slightly from the other scenarios by having two equal and rather small charges, each giving a hazardous distance of 2.95 m. The distance between the two charges is 2 m, and is thus comparable to the individual hazardous distances. In this scenario, the "true" hazardous zone looks like two overlapping circular zones, with a small lobe due to the interacting blast waves (Figure 4.3). An approximation where we assume these two charges as one positioned in the centre of mass (which will result in a circular zone) is thus not a good approximation. In fact, Approximation 1 is somewhat special made for a situation like this. However, the method does not take the lobes generated by the interacting blast waves into account. It underestimates the hazardous distance by roughly 7 %, however the area of the "true" hazardous zone left outside is only 1 %.

In all other scenarios, the hazardous range of the dominating charge is larger than the distance between the two charges (d). The resulting hazardous zones are more or less circular, with some small deviations due to the interacting blast waves. Hence approximating the hazardous range by one charge in the CoM is therefore generally a very good approach. This favours Approximation 2.

Approximation 3 seems to give results sandwiched between Approximation 1 and 2. In terms of reflecting the true hazardous zone, this is the optimum choice as the approximate hazardous zone equals the true hazardous zone.

What is the best approximate procedure? This question cannot be answered unless an upper acceptable limit of the error is given. However, based on the scenarios assessed in this report, the following rule of thumb could be given. By choosing the maximum of $r^{(1)}$ and $r^{(2)}$, that is the maximum hazardous range given by Approximation 1and 2, respectively, we obtain the smallest part of "true" hazardous zone left outside the approximate hazardous zone.

4.3.2 A pragmatic approach

When assessing the probability of having an injury due to one or several detonating blast sources, there is seldom a need for a resolution down to centimetres or even decimetres. Hence a conservative and practical approach would be to round the hazardous distances up to, say, nearest meter. As seen in the previous subsection, all approximations underestimate the "true" hazardous range. Thus, to round up will reduce the error (amount of "true" hazardous zone left outside the approximate hazardous zone).

The results, after rounding the approximate hazardous distances up to nearest meter, are seen in Figure 4.10 (area) and in Table 4.4 (distances).

For Scenario 1, all approximations overestimate the true hazardous distances, but not with more than 5 %. Approximation 2 also overestimates the hazardous distances for Scenarios 3 and 4, but by no more than 8 % and 6 %, respectively. Hence, these approximations are fairly accurate. Thus, we can conclude that by choosing the maximum hazardous distance from Approximations 1 and 2, the error is kept at a minimum without significantly overestimating the hazardous distance.

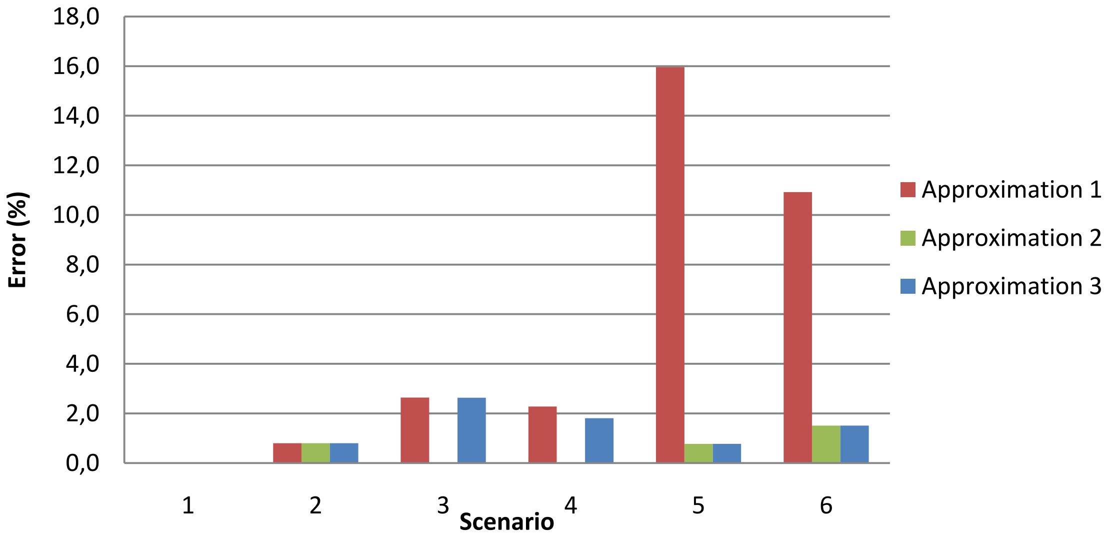

Figure 4.10 Error (amount of "true" hazardous area outside the approximate zone) after the approximate hazardous distance is ***rounded up*** *to nearest meter.*

Table 4.4 Same as Table 4.3, however, the hazardous distances are ***rounded up*** *to nearest meter. Deviations from the "true" hazardous range are indicated.*

Scenario	*AUTODYN*	*Approximation 1*		*Approximation 2*		*Approximation 3*	
	True haz. range (m)	$r^{(1)}$ *(m)*	*Deviation (%)*	$r^{(2)}$ *(m)*	*Deviation (%)*	$r^{(1)}$ *(m)*	*Deviation (%)*
1	3,8	4	5	4	5	4	5
2	4,3	4	-6	4	-6	4	-6
3	8,4	8	-4	9	8	8	-4
4	8,5	8	-6	9	6	8	-6
5	9,4	8	-15	9	-4	9	-4
6	9,3	8	-14	9	-3	9	-3

5 Conclusions

Three methods for approximating the hazardous range for a situation with two detonating charges have been compared to the "true" hazardous distance found by numerical simulations. Two of the approximate methods are based on the hazardous distance found for single charges, whereas one approximation is based on transforming the true hazardous area (zone) into a circular hazardous area (zone).

The true hazardous zones are in general not circular due to the interaction of the two blast waves. In most cases, the highest pressure levels found is either in the direction of the axis connecting the two charges, or perpendicular to it. However, this may not be true in general.

First we evaluated the actual physical outputs from the three approximations. Then we compared the results after rounding the estimated hazardous distances up to the nearest integer meter, which is a more pragmatic approach from an actual testing point of view.

The physical outputs demonstrated an underestimation of the "true" hazardous distance for all scenarios and all three approximations. The amount of "true" hazardous area left outside the approximate circular hazardous zones varies with the approximation procedure. The error is less than 20 %. By selecting the maximum value of the hazardous distances found by Approximations 1 and 2, $r^{(1)}$ and $r^{(2)}$ respectively, the scenarios tested in this report give errors less than 2 %!

The more pragmatic approach gives an increase of the approximate hazardous distances. For some combinations of scenario and approximation procedure, the hazardous distances were overestimated, but by no more than 8 %. Again, by selecting the maximum of $r^{(1)}$ and $r^{(2)}$, the errors are still less than 2 % for Scenarios 2, 5 and 6. For Scenarios 1, 2 and 4 the entire "true" hazardous zones are included in the approximate hazardous zones, hence the errors equal to zero.

Both the physical outputs and the more pragmatic approach yield an accuracy which is far better than the uncertainty in experimental work. The pragmatic approach is a conservative approach.

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