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SHAPED CHARGE CALCULATION MODELS FOR EXPLOSIVE ORDNANCE DISPOSAL OPERATIONS

Abstract

The clearance of unexploded ordnance (UXO) and other explosive remnants of war (ERW) containing shaped charge warheads poses a particular technical hazard to consider for explosive ordnance disposal (EOD) personnel. The wide use of light anti-tank weapons, such as rocket propelled grenades and the scattering of sub-munitions in different conflict areas have made the clearance of shaped charge ammunition a frequent task. However, unlike other hazards, for shaped charges, EOD personnel lack adequate means for the establishment of the maximum hazardous area and for the design of measures for hazard confinement against the shaped charge effect.

In this article two different models are suggested, which together give guidance for protective measures during clearance of shaped charge ammunition. The development of these models is based on their military utility, by consideration of the limited information availability, the short time frames, the working methods and the technology level that are characteristic for EOD operations. The two suggested models are developed further into a complete set of design rules for protective measures, giving a versatile tool to replace today´s rough estimates and guesswork, in these safety-related decisions.

Keywords

shaped charge, jet penetration depth, hazardous area, explosive ordnance disposal, protective measures

Introduction

Ammunition with shaped charge effect is a separate technical hazard in EOD operations. The EOD officer is required to consider an extended hazardous

area for the jet, design possible measures for hazard confinement based on its higher penetration, and, if possible, choose a render safe procedure that prevents the jet from developing. The problem is that the EOD officer to a large extent is without scientific support to determine how the shaped charge effect affects these protective measures.

In the current situation, Swedish EOD personnel are mainly using three sets of calculation models; a Swedish model developed by the Swedish Defence Research Agency (FOI), the UN's model and NATO's ditto. What model is used depends on what is regulated in standard operating procedures (SOP) for the operation and under what mandate the clearance is carried out. Common to these models is that they give no support in estimation of the shaped charge effect.

Shaped charge ammunition is a frequent clearance task for EOD units and occurs primarily as rocket propelled grenades to light anti-tank weapons, sub-munitions and landmines, but can actually occur in most ammunition types, from simple hand grenades to missiles.

The overall purpose of the work presented here is to create a "tool" that can be used in the design of protective measures for clearance of shaped charge ammunition. Tools to consider may be mathematical formulas, tables, graphs or other appropriate support. The military utility is decisive, which means that results must be useful based on the needs and objectives of the organisation. The result is expected to contribute to decision making that is based on scientific support and to derivable conclusions. Today, EOD personnel are forced to rough estimates, at best based on experience from similar situations. In the end, this is about forming an enhanced safety in connection with EOD operations, both for the clearance personnel and for third person. Furthermore, it is about protecting economic and material values.

Extensive research has been conducted for many years regarding shaped charge jets. However, specific research on calculation models for protective measures for clearance operations is nearly non-existent. The central point of this article is on determining whether calculation models from other areas are applicable, directly or with some adaptation, to EOD operations.

Two important subdivisions are identified, to which EOD service currently lacks models or other appropriate support for decision making. The first subdivision relates to tools for the design of measures for hazard confinement, which are established to reduce or eliminate the effect of the jet. This serves as basis for decisions regarding which dimensions are necessary to prevent the jet from penetrating a protective structure, given the choice of structural materials and placement. The second subdivision relates to tools for estimation of maximum hazardous area, which an unaffected jet can cause. The purpose is to create a basis for decisions regarding the extent of evacuations and cordon.

In this article, based on a military technology thesis (Johnsson), two different models are suggested, which together give guidance for protective measures during clearance of shaped charge ammunition

The first model is intended for use in the design of measures for hazard confinement against jet penetration. The suggested model is derived from a combination of two existing models for the shaped charge effect. A model for shaped charge penetration in single layered media developed by the Swedish Defence Research Agency (FOI) is used as the basis for the model. This is then combined with a modified model that describes how the penetration depth decreases with an increasing stand-off distance. Together they give a simple model for calculating the minimum thickness of barricades and mounds to withstand the penetration of shaped charges at varying distances.

The second model is for estimation of the maximum hazardous area generated by the shaped charge jet. This calculation model is based on the trajectory of the most critical jet segment, i.e. the slug. By defining typical values for those parameters that EOD personnel normally do not have information about, this model can be described with a simple graph. The graph gives the maximum hazardous area based only on the calibre and the elevation of the ordnance. The slug may be stable or unstable in its trajectory - the former giving a significantly larger hazardous area. As the conditions for or the probability of which will apply in a particular case is, currently, not supported by adequate scientific data, figures are given both for a stable and a tumbling slug segment. The use of the figures for an unstable slug will lead to a smaller area at the expense of higher risk.

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Generally, a distinction is made between two main types of shaped charge technologies: shaped charges (SC) and explosively formed projectiles (EFP). The article discusses the shaped charge technology and is not applicable to EFP, because of the fundamental difference in principles of action between the two technologies.

EOD Operations

Protective Measures

Explosive ordnance disposal operations is a generic term for all activities designed to restore freedom of movement when personnel, equipment, installations or operations are affected by suspected or confirmed presence of explosive ordnance (Swedish Armed Forces 2004 [1], abbr. SwAF 2004 [1]). One activity within EOD operations is protective measures and refers to those measures which aim to reduce the technical hazards of the ammunition. Similarly defined are counter mine operations, when the ammunition which is cleared consists of landmines. Regarding protective measures, which is the focus of this article, there is no significant difference and further work can also be considered applicable to counter mine operations (SwAF 2004 [1]).

The EOD officer is responsible for all clearance activities at a site. In addition to the command of the clearance he/she also has the responsibility for protective measures. When tasking EOD operations the incident category of the task is established. This is a measure of the acceptable risk of clearance personnel, third person, national/operational safety and operations. Typically, the operations are in the lower risk-taking levels, with some general safety principles applied. E.g. technological and methodological choices shall be made in a way that minimizes the risk for clearance personnel, third person, equipment and environment. Further, the EOD officer is required to analyse the worst case scenario and take steps to limit possible adverse effects (SwAF 2004 [1]).

The clearance procedure

At an early stage of a clearance operation the EOD officer makes an initial assessment of the ammunition. At this point the technical hazards which could lead to harmful effects, including shaped charge effect, are assessed.

The initial assessment is the basis for where the control point will be located and the need to take immediate actions. During the operation the technical risk assessment is refined when more information about the ammunition is obtained, e.g. by reconnaissance or information gathering.

An estimation of the hazardous areas from contact effect, blast effect, ground shock effect, effects of fireball and heat radiation, fragmentation effects and secondary fragments from the surface and surroundings is made. The aggregated hazardous area is normally the area that is the subject to cordon and evacuation. Calculations of the hazardous area are also the basis for an overall picture of potential damage and where unacceptable damage is expected, the effect is reduced through the establishment of measures for hazard confinement. As with the technical dangers, the EOD personnel must normally make an initial assessment of the extent of the hazardous area, which is later refined. The measures for hazard confinement are based on calculations of the type of effect or effects to be reduced and normally constructed from temporary construction materials as sandbags, timber or water-filled cans. (SwAF 2004 [2])

The hazardous area at explosion can for most effects be described as a hemisphere with the ammunition in the centre, see Figure 1(left).

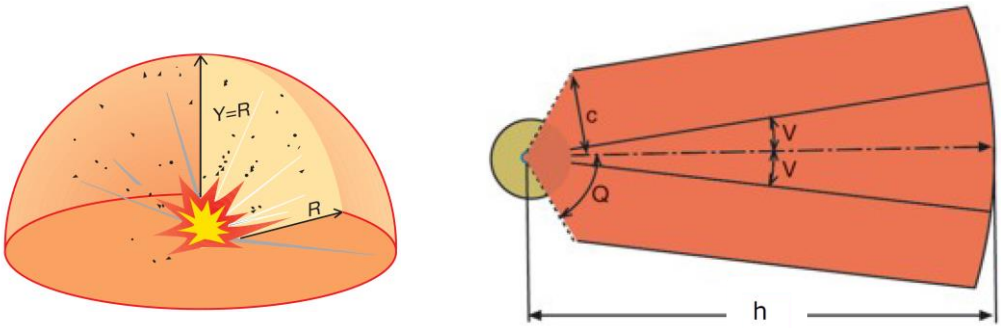

Figure 1. Hazardous area at explosion (left) and for shaped charge effects (right). (SwAF 2004 [2])

For shaped charge effects, a hazardous area is also developed in the line of fire due to the jet's features, see Figure 1(right). In this case, the hazardous area is not considered a hemisphere but a sector with a risk range in length (h), risk angle for deviation to the sides (v), the risk angle for ricochets (Q)

and risk distance for ricochets (c). The EOD officer must take into account the increased hazardous area for the jet. (SwAF 2004 [2]) However, unlike all other kinds of effect there are no calculation models or other appropriate assistance for these safety-related decisions. The only available support (in Swedish handbooks) for the hazardous area of a jet is two pieces of shaped charge ammunition for which the hazardous areas is given. (SwAF 2004 [3]) These have calibres of 20 and 33 mm and cannot be considered to be representative of common unexploded ordnances and are therefore considered to be of limited value as guidance for clearance of other shaped charge ammunition.

Operational requirements

Based on the description of EOD operations above and based on the main author's personal experience, the following operational requirements are considered to be relevant to consider.

- **Complexity.** Necessary calculations shall be possible to perform on a calculator, which is part of the reconnaissance equipment for EOD units. Furthermore, the mathematical complexity should not exceed the level of secondary school, which can be regarded as a general minimum requirement for EOD officers.

- **The time factor.** A tool that identifies the size of the hazardous areas and measures for hazard confinement should allow for rapid assessment on the basis of limited information access. The purpose is to serve as decision support regarding the need for immediate action at initial assessments. The tool should also allow for more refined assessments/calculations if needed.

- **Information access.** The calculation model should be based upon the technical information that is normally available concerning unexploded ordnances. It should also be possible to estimate the relevant parameters even if a complete identification is not possible or if the information on the individual item is defective. In these cases, the information should be derivable from general ammunition knowledge and technical reconnaissance results.

- **Simple construction solutions.** The solutions for hazard confinement shall be so simple that they can be established with temporary

construction materials and without access to special equipment. At the same time they shall be designed to be integrated into an overall solution consisting of a combination of measures against different effects.

Shaped charges

Basic principles

A shaped charge is often made as a cylinder filled with explosive, a detonator at one end and a hollow cavity with a metallic conical liner at the other. On detonation of the explosive, the conical liner collapses into a metallic jet with a very high speed (several thousand meters per second). The last part of the jet, the slug, has lower velocity. The jet may penetrate to large depths – several times the charge diameter. Penetration depth is often given in charge diameters (CD), see Figure 2. The maximum penetration capacity for shaped charges was 2-3 calibres during WWII and is as much as 12 calibres today. (Hansson et Westerling)

The penetration of a shaped charge increases with the jet length and density and decreases with higher target density. A drawing of a shaped charge is shown in Figure 2.

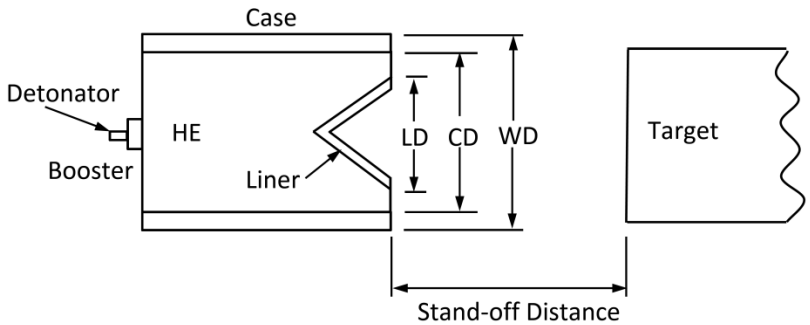

Figure 2. Shaped Charge (Walters et Zukas).

Penetration depth

Theoretical studies as well as experimental research have led to the development of advanced models for the calculation of penetration depths, (Walters et Zukas). For these models, however, detailed knowledge of data of the jet characteristics as well as the target material are necessary – data which

usually are not available for clearance of shaped charge ammunition nor are resources needed for the execution of such models readily available for the clearance team. For such situations robust and reliable easy-to-use methods are needed.

In Sweden, a simplified model for penetration into fortifications has been developed by FOI, (Elfving et al) and is used in the Swedish Design Manual for Protective Construction, FKR2011, (Swedish Fortification Agency [1]). The depth of penetration, *H*, is calculated as:

$$H = \emptyset \times k_1 \times k_2 \times \sqrt{\frac{\rho_{jet}}{\rho_{target}}} \qquad \text{(Eq 1)}$$

Where	H	Depth of penetration	(mm)
	$\emptyset$	Warhead calibre	(mm)
	k_1	Coefficient for jet length (Table 1)	(-)
	k_2	Coefficient for target material (Table 2)	(-)
	ρ_{jet}	Jet density	(kg/m^3)
	ρ_{target}	Target density	(kg/m^3)

Warhead	**Calibre [mm]**	$\boldsymbol{k_1}$
Sub-munition	< 70	8
Hand-held anti-tank weapons	< 110	8/12/16*
Light anti-tank missiles	< 130	12/16**
Heavy anti-tank missiles	< 180	12/16**
Ballistic missiles	< 350	12/16**
* k_1= 8 is used only for older ammunition with a depth of penetration into steel up to 4 diameters, else k_1 = 12. ** k_1= 12 is used for all munitions, except late versions, with a depth of penetration into steel corresponding to 8 calibres.		

Table 1. Coefficient, k_1, for jet length.

Target material	**Density, appr. [kg/m^3]**	$\boldsymbol{k_2}$
Sand, gravel	1600	1,0
Ordinary concrete (C40)	2400	0,8
High-strength concrete (C140)	2500	0,5

Table 2. Coefficient for target material, k_2.

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Equation 1 is developed for protective purposes, why it is based upon optimal performance of the ammunition. For shaped charges a distance from the warhead to the target is needed for maximum penetration. Warheads are therefore designed to detonate at a certain distance from the target, the stand-off distance, see Figure 2.

The penetration versus stand-off for ideal jet performance for a shaped charge with a conical layer with a maximum penetration depth of 8 diameters according to Walters and Zukas is given in Figure 3.

Now, more advanced designs have been achieved through e.g. modified liner shapes. Still, though, the principal shape of the curve penetration vs. stand-off distance has shown to hold true (Wijk et Tjernberg).

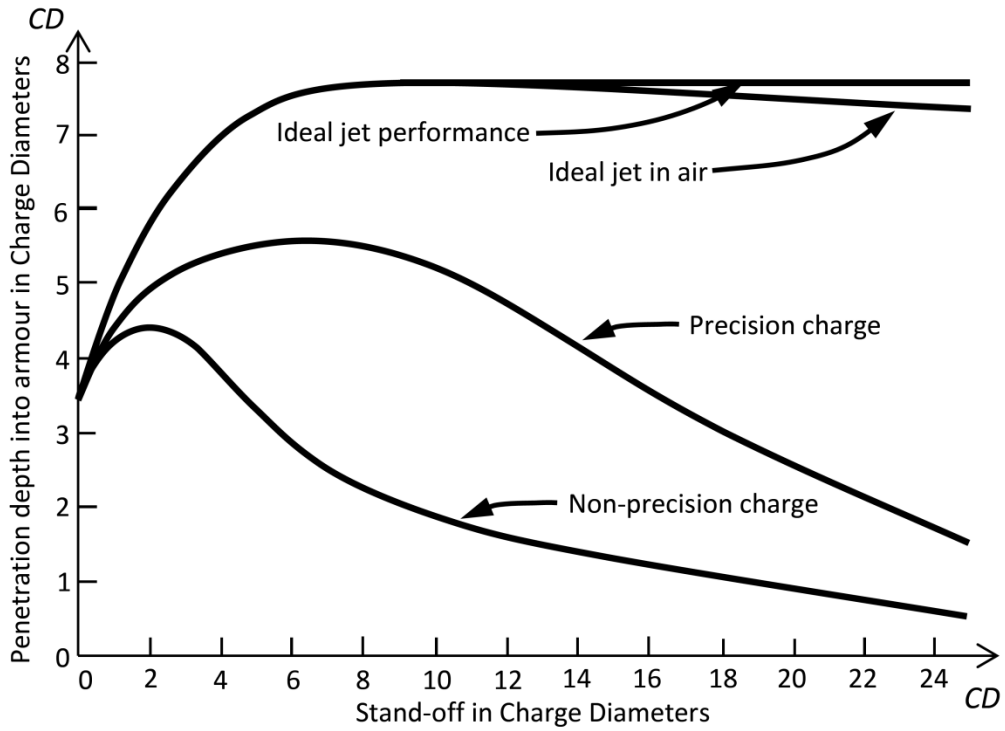

Figure 3. Stand-off-curves for precision- and non-precision charges. Penetration into 320 BNH armour as a function of stand-off distance, both expressed in charge diameters, CD. (Walters et Zukas)

The stand-off curve in Figure 3 is for armour. However, there are no reasons to believe that its principal shape should not apply also for other target materials.

Wijk presents two simple formulas for the non-dimensional penetration one for precision and another for non-precision charges (Wijk):

$$P = \frac{5{,}6C}{1 + \left(\frac{S - 7C}{14C}\right)^2} \qquad \text{(precision charges)} \qquad \text{(Eq 2)}$$

$$P = \frac{4{,}5C}{1 + \left(\frac{S - C}{8C}\right)^2} \qquad \text{(non-precision charges)} \qquad \text{(Eq 3)}$$

Where P Depth of penetration
S Stand-off distance
C Calibre
P, S and C should be in identical units.

They fit well with the stand-off curves, though they do not cover warheads with penetrations above the curves. For these, however, as the shape of the curve is not significantly changed, Equation 2 should be applicable.

Model for calculation of penetration depth

It should be possible to modify Equation 1 for use also for EOD purposes in relevant materials as it is based upon parameters normally available to the EOD personnel by introducing ways to handle these construction materials and accounting for non-optimal stand-off distances in the formula.

Construction materials often consist of sand in sandbags and similar material data for such materials should be used. The coefficient for material, k_2, ideally, should be given also for water, wood and different soils. The model also accounts for the technical development of the penetration capacity for new shape-charge designs through the coefficient for the length of the jet, k_1.

The information needed for calculations are in most cases available through ammunition databases. Even if detailed data is not readily available, estimates based on general knowledge about ammunition and from reconnaissance may well be adequate.

For measures for hazard confinement the optimal stand-off distance is usually not relevant. For these, a safety distance is normally used between the device and the measures i.e. to avoid contact with it which leads to larger distances than the optimal for penetration. As this distance may have a substantial influence on the penetration it should be accounted for to avoid overly conservative values for *H*.

Equation 2 uses calibre, detonation distance and precision of manufacture. The first two parameters may be measured on the site and the precision may be estimated by the EOD team.

According to Walters and Zukas, the standoff-curve is scalable and applicable for charge diameters in the range of 40-178 mm. This is of importance for ammunition clearance as the same is relevant and can be used for different devices to be destroyed.

This leads to introducing a factor $k_{distance}$ for reduction of penetration depth as a function of stand-off distance in non-dimensional format:

$$k_{distance} = \frac{1}{1 + \left(\frac{S - 7C}{14C}\right)^2} \qquad \text{(Eq 4)}$$

Where	$k_{distance}$	Coefficient for stand-off distance	(-)
	S	Stand-off distance	
	C	Calibre	
		S and C should be in identical units.	

The equation leads to a curve as shown in Figure 4. A comparison was made between the proposed factor and available test data for different stand-off distances (Johnsson). The model shows good agreement with these data as shown in Figure 4.

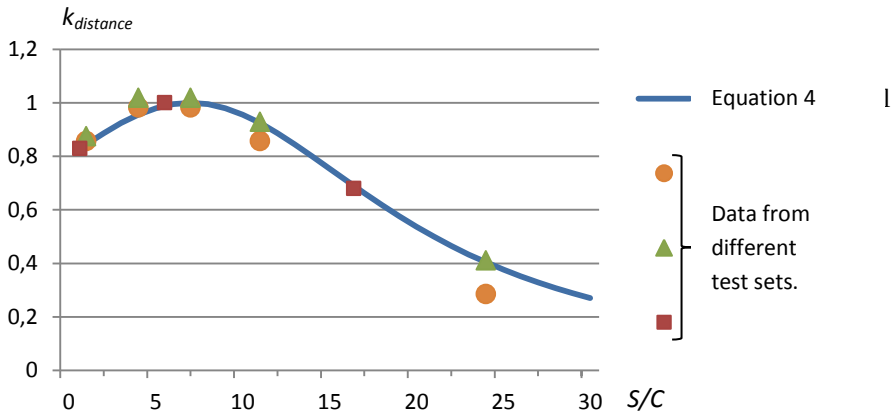

Figure 4. Plot showing the proposed coefficient for detonation distance, $k_{distance}$, as a function of the ratio ***S/C*** and compared with test data, introduced by Johnsson.

A model for calculation of measures for hazard confinement should account for both penetration capacity in different materials and the stand-off influence.

Therefore, two models are suggested to be integrated into one according to:

$$H = \emptyset \times k_1 \times k_2 \times k_{distance} \sqrt{\frac{\rho_{jet}}{\rho_{target}}} \qquad \text{(Eq 5)}$$

Model for required thickness of measures for hazard confinement

Equation 5 does not address sources of error in dimensions, target material properties and non-homogenous construction through the use of sandbags etc. why a safety-factor should be included in the formula

Demolition of ammunition, normally, is made by clearance charges or disrupters used against the device, which leads to a non-ideal jet e.g. the penetration according to the formula is on the conservative side, the degree of conservatism, though, difficult to put number on.

Swedish Fortification Agency uses factor ξ in accounting for what damage to the structure is acceptable (level of function) and what are the requirements

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on the protective structure (level of protection). (Swedish Fortification Agency [2])

Using the same approach for handling these uncertainties leads to the formula for required thickness, H_d,:

$$H_d = \emptyset \times k_1 \times k_2 \times k_{\text{distance}} \times \xi \sqrt{\frac{\rho_{jet}}{\rho_{target}}} \qquad \text{(Eq 6)}$$

The suggested model should be applicable for design of measures for hazard confinement for EOD operations. The model is applicable for relevant materials and the influence of stand-off distance.

Comparisons with experimental data show good agreement (Johnsson). The factor ξ gives a safety margin for minor misjudgements and deviations in measures etc.

For the use of the formula for damage-protection tentatively, a factor ξ=1,3 is suggested.

The use of the model should be limited to shape charge warheads with calibres 40-178 mm and for stand-off distances less than 25 calibres. These restrictions, however, should be of minor concern as the formula covers shaped charges in the overwhelming majority of cases and the stand-off distance should be more than adequate for practical purposes.

The stand-off distance from the calculations could be used to estimate the cost-effectiveness of different designs for damage-reducing measures.

A tool for design of measures for hazard confinement

The model is based on information that the EOD personnel normally have access to by ammunition databases or can estimate even if the ammunition cannot be completely identified. The complexity is considered reasonable and is in this context mathematically not more difficult than models used for calculation of e.g. fragmentation effect. Despite this, the efforts should be to

find even simpler tool that is better suited as a point of reference in stressful situations where there are no time and opportunity of formula calculations.

A simpler tool, such as a table or a graph, can be created if the number of variables can be reduced. For example, copper is the dominant liner material in shaped charge warheads and sand in sandbags is the most common construction material in measures for hazard confinement. Based on these values, representing a typical normal case, the following more easy to use graph has been constructed.

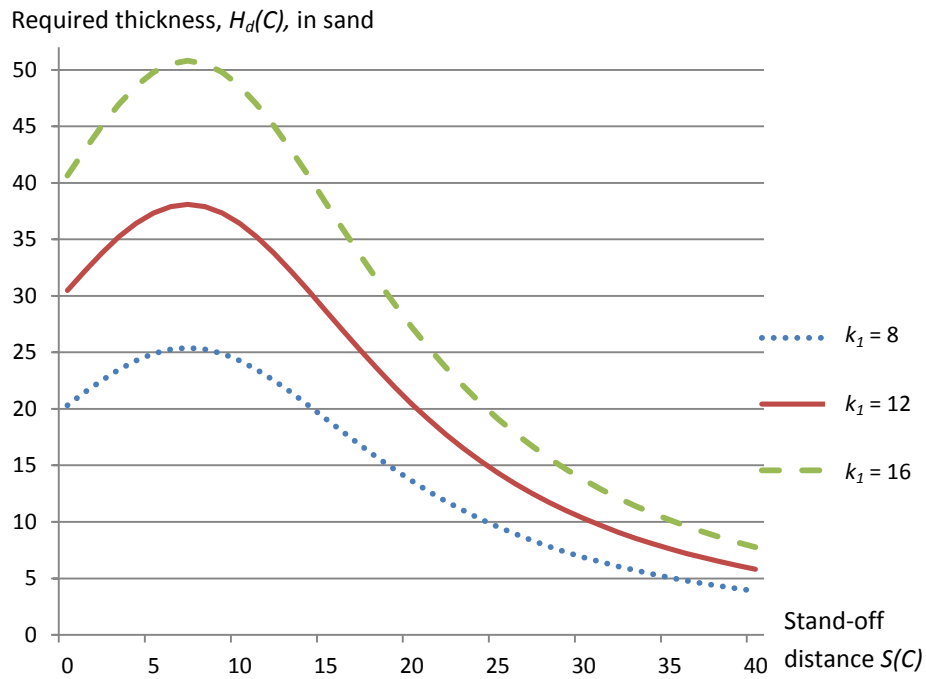

Figure 5. Suggested tool for design of measures for hazard confinement constructed in sand. The graph indicates the required thickness, H_d, (in sand) as a function of the stand-off distance, both expressed in the number of charge diameters. The curves in the graph include the factor, ξ=1,3, and refer to different values of the coefficient of jet length, k_1 (according to Table 1).

Besides the thickness, the measures of a barricade should be so large that it will catch the jet even at some side or height deviation. Furthermore, they should include sources of errors related to the estimation of the jet's direction and ensure that the barricade still has a sufficient thickness if the warhead is

slightly displaced. A margin of 200 mils ≈ 11.5 degrees is considered relevant, which corresponds to the deviation to the sides applied in the design of hazardous areas during firing (SwAF 2010 [1]). At a maximum stand-off distance of about 25 calibres, this corresponds to about five calibres margin. To simplify the construction and to avoid the risk of obtaining low margins on short stand-off distances it is suggested that the margin five calibres is applied regardless of stand-off distance. This means that the barricade should be about ten calibres wide and about five calibres above the predicted point of impact. If there is a risk of ricochet on this side of the construction it is suggested that this will be handled according to the same principle which applies to clearing charges containing shape charges, as the width and height of the protective measures are extended based on type of soil in the ground,(SwAF 2004 [3]).

For other kinds of effects of the unexploded ordnance and possible clearance charges, the regular dimension criteria apply for each measure for hazard confinement. This means that in some cases, there is a need to combine several measures for hazard confinement and the measures described above must not fall below in that part of the construction which is intended to prevent jet penetration.

Render safe procedures typically, e.g. clearance charges, imply that the ordnance is subjected to a force which may affect its physical location. In addition, the energy of the render safe procedure can initiate the shape charge, which might result in an asymmetric detonation front from an offset initiation point. In both cases, the effect being that the jet receives a slightly offset point of impact. To minimize this theoretical risk of displacement all render safe procedures should be applied from above. In case you do not want a perpendicular angle of attack, the angle should be applied in the vertical plane. In this way one must consider a motion or initiating related displacement of the jet as a drift towards the ground.

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Maximum throw distance for estimation of risk area from undisturbed jet from shaped charges

For calculation of the maximum throw distance from a shaped-charge jet by ballistic methods data on initial velocity, elevation-angle, mass and air-drag for fragments must be known (Carlucci et Jacobson).

The air-drag may be calculated as:

$$D = C_D \times A \times \rho \times \frac{V^2}{2} \qquad \text{(Eq 7)}$$

Where	D	Air-drag force	(N)
	C_D	Air-drag coefficient, depending on fragment shape, velocity and orientation	(-)
	A	Fragment area perpendicular to trajectory	(m^2)
	ρ	Air density	(kg/m^3)
	V	Fragment velocity	(m/s)

The trajectory may be calculated, approximately, from Newton's second law of motion for a point-mass:

$$m\frac{dV}{dt} = D + mg \qquad \text{(Eq 8)}$$

Where g is the vector acceleration of gravity.

However, as the opposing force from the air-drag is depending on the velocity, a closed form solution is not possible and numerical procedures are necessary. With adequate computer programs the position, direction and velocity of fragments may be calculated. It is beyond the scope of this article to go in detail concerning the calculations.

A model for maxim throw distance for estimation of maximum hazardous area at clearance of ammunition used must be considerably simplified. First of all, it should be adapted to the information normally available to or that could be estimated by the EOD team. Secondly, it should be possible to

perform the calculations without access to advanced computer support and specific computer software.

This may be achieved by identifying typical values (e.g. characteristic of most shaped-charge ammunition) for typical parameters to address the situation for specific objects.

A study of the jet creating the maximum hazardous area shows that beyond the optimum stand-off distance it starts to disintegrate into separate segments. These segments may vary in size and shape and due to the gradient of the jet also the velocity may differ. Each part of the jet may give a maximum hazardous range based on the characteristics of that particular segment. For more accurate calculations of the range these must be based upon data relevant to each jet segment. The last part of the jet, the slug, normally, gives the largest hazardous distance (Harling).

The mass of the slug has been set to 75% of the mass of the liner. The velocity of the rear part of the jet is substantially lower than the velocity of the tip of the jet. The calculations are based upon a slug velocity of 700 m/s.

The shape of the lining influences the mass and how much material that creates the slug. A rectilinear conical shape with the angle 40 degrees is typical for most shaped charges.

The thickness of the liner is set to 3% of the cone diameter and made from copper with a density of 8950 kg/m^3.

Data from rectilinear conical liners are used in the approximation. More advanced shapes for penetration focus on tip velocity and less on the slug, which is in support of the approximation.

The air-drag coefficient, C_D, accounts for shape and the projected area. The air-drag coefficient for a slug is used in the calculations in the following:

Fragment shape	Velocity range 0,1-0,9 Mach	Velocity range 0,9-10 Mach
Fragment from HE rounds	0,91	1,21

Table 3. Air-drag coefficients for fragments (Janzon).

The shape of the slug may vary from spherical to almost cylindrical or conical. In addition, it's of importance if the slug is stable in the trajectory with tip in front or not stable, tumbling. Unfortunately, there seems to be no data to support what is the actual performance of ejected slug elements. This may influence the maximum throw significantly.

For a stable, cylindrical fragment the projected area could be calculated as

$$A = \pi d^2/4 \qquad \text{(Eq 9)}$$

and for a tumbling fragment an average value calculated from the total fragment area could be calculated as (Janzon):

$$\bar{A} = \frac{S}{4} \qquad \text{(Eq 10)}$$

Where $\bar{A}$ Average projected area
S Total area

Both formulations have been used in the subsequent calculations.

Data show, that the slug, typically, is cylindrical in shape with a length over diameter ratio of about 1-3. Data on the slug shape in clearance operations are not available to and cannot be concluded from observations on site by the EOD team. An estimate must be made.

For a tumbling slug, the lower value may be used but for a non-tumbling slug the higher value is more relevant.

For the calculations in the following, an average value for the length over diameter ratio of 2 has been used. The average area for a tumbling slug is then (Janzon):

$$\bar{A} = \frac{\pi d^2 + 2\pi dh}{8} = \frac{5\pi d^2}{8} \qquad \text{(Eq 11)}$$

Where $\bar{A}$ Average projected area
d Cylinder diameter
h Cylinder height = $2d$

The only two remaining parameters, elevation angle and calibre, can be measured on site and are key factors for the calculation of maximum hazardous range. Computation is now possible if the other parameters are based upon typical values, as discussed above.

There is a difficulty in verifying the computed data as test data are very limited. Also the spread in data due to assumptions on properties of the ejected slug are significant. (Moss)

A tool for estimation of maximum hazardous area

The suggested model of an undisturbed shaped charge jet's maximum range is, despite the use of typical values, still limited useful in EOD operations. The reason is the complexity of performing the calculations necessary, which is beyond what the EOD team has resources to handle. Further simplification is required to obtain a tool adjusted to its operational purpose.

When the number of unknown variables to calculate the maximum hazardous area in the previous step is reduced to calibre and elevation angle, it is possible to illustrate the calculation model with a graph. The graph for each calibre indicates the maximum hazardous area for an undisturbed shape charge jet as a function of the elevation angle.

Figure 6 assumes that the slug tumbles in the trajectory and Figure 7 assumes that the slug is stable in the whole trajectory.

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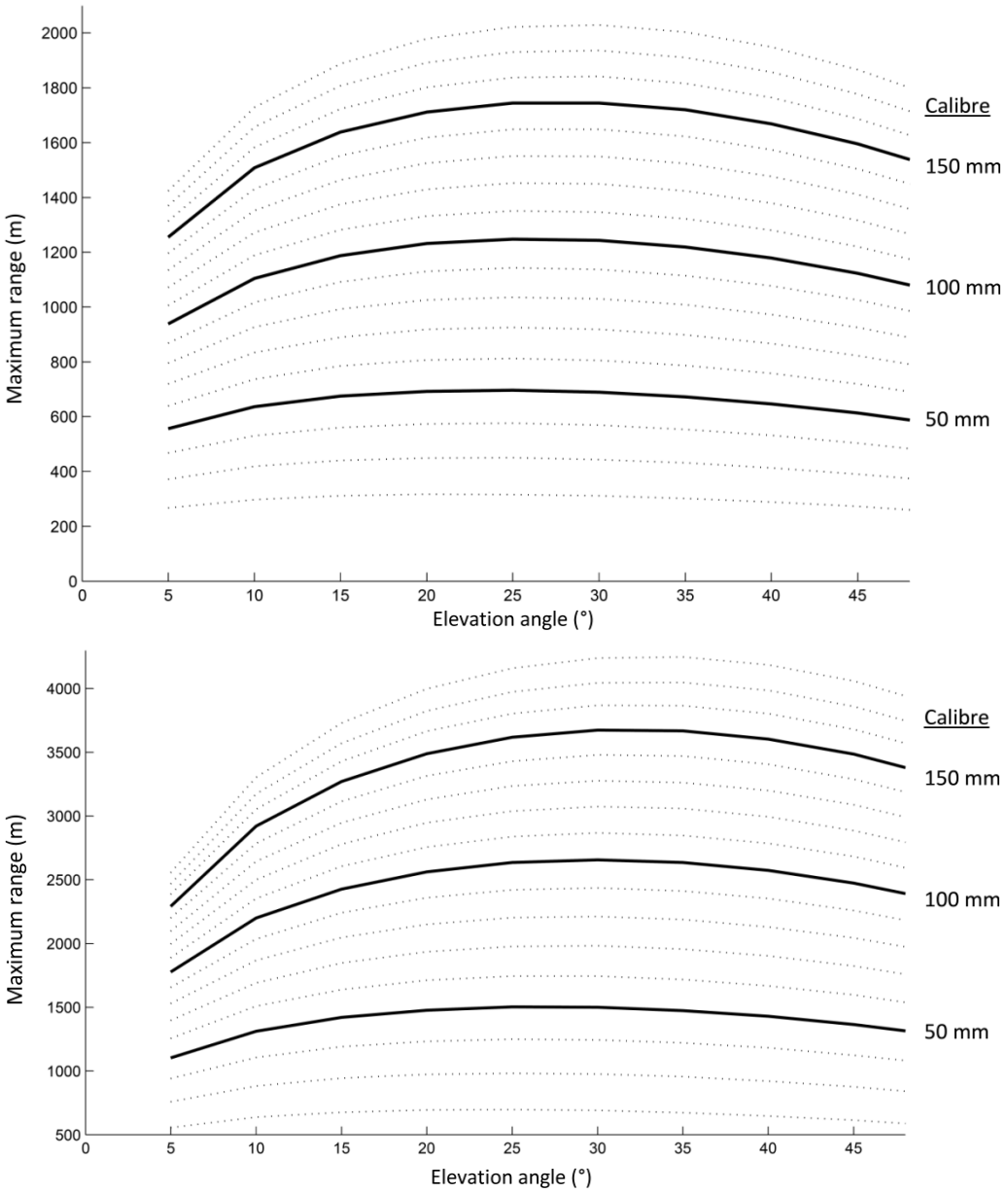

Figure 6 & Figure 7. Maximum hazardous area for un undisturbed shaped charge jet as a function of elevation angle, for calibres between 20 and 180 mm, for a tumbling slug segment in Figure 6 (top) and for a slug with a stable trajectory Figure 7 (bottom). The calculations are based upon a level of 500 m above the sea.

Apart from the length of the hazardous area, (*h*) the dimensions of the width and height must also be defined. As discussed in the previous section, a risk angle for deviation to the sides (*v*) of 200 mils should be used. The risk of ricochet is to be handled in the same manner as for clearing charges with shaped charge warheads. The risk angle of ricochet (*Q*) is set to 1000 mils and the risk distance sideways related to the ricochet (*c*) is according to standard procedures. (SwAF 2010 [2])

The height of the trajectory is dependent on the elevation angle and the greater the angle, the higher the altitude for the slug. It's suggested to use 0.5*h* for all elevation angles 0-45°.

The hazardous area for the jet adds to the hazardous areas from other effects, in the direction of the jet.

The risk that the render safe procedure influence the object's position is regarded in the same manner as discussed for measures for hazard confinement.

The tool for estimation of the hazardous area for an undisturbed shaped charge jet here comes in two versions, one for a stable and one for a tumbling slug. It is suggested to use the worst-case scenario according to Figure 7, unless the uncertainties concerning tumbling are been resolved.

Risk considerations

Risk is often taken as probability multiplied by consequence. The major consequence of concern for clearance operations is most of the time injuries/death of personnel. For EOD operations the probability of event is one parameter, the effects from a detonation another and the likelihood that individuals are exposed to these effects a third.

In clearance operations, the probability of event is very difficult to identify. A focus on potential consequences may then have to be a substitute.

When looking at consequences associated with clearance of shaped charges, a sharp line around a hazardous source to indicate an area to delimit access may give the impression of a safe area at the outside and an unsafe area on

the inside. In reality, though the line is not sharp and the consequences could vary much also within the identified hazardous area.

The size and the shape also depend on assumptions made in calculations. The distances in Figure 6 and Figure 7 are based on an initial slug velocity of 700 m/s. A higher assumed velocity leads to larger area.

In the case of a high velocity slug a direction close to horizontal will be stopped by hitting the ground or obstacles on it quickly. With a higher elevation it will travel further giving higher consequences at large distance where it hits ground but very small consequences at intermediate distances.

In addition, higher risks must be accepted for key personnel, e.g. the clearance team. For third party additional measures may be necessary to lower risks.

This means that the use of the tools is very much up to good judgment by the EOD officer.

Much work remains to be done to quantify consequences from a potential clearance activity. Advanced methods have been used to originate easy-to-use tools for storage of ammunition on an international level. Results from this work could be used also for regulation of clearance operations (NATO AASTP-5).

Conclusion

To fulfil urgent military needs, two separate tools are suggested for the design of measures for hazard confinement and for the estimation of the maximum hazardous area, which together create a basis for protective measures against shaped charge effect.

It is shown how it is possible with limited information about a shaped charge and with use the suggested tools estimate the maximum penetration into a protective construction as well as the maximum hazardous area from the jet from a shaped charge.

The tools are adapted to the limited information availability, the short time frames, the working methods and the technology level that are characteristic for EOD operations. The military utility of the result is considered high as it

creates a scientific basis for decision making, in contrast to today´s rough estimates and guesswork in these safety-related issues.

More research is necessary to fine-tune these tools.

One additional conclusion of the work is that the slug may create risks even at very large distances. A priority for the clearance team should therefore be to eliminate this risk by choosing a suitable render safe procedure in combination with adequate measures for hazard confinement.

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[1] This publication has been replaced by a revised edition in Swedish, regarding this subject there are no significant differences

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