SWERISK – Fast calculation of risk in EOD operations

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ABSTRACT

SWERISK is a computer model for calculating the probability of a human being hit and injured by fragments from a detonating warhead in explosive ordnance disposal (EOD) and demining operations. It was from the outset intended as a field instrument to support the crucial task of quickly determining how large an area must be sealed off to minimize the risk to own troops and civilians, and for estimating the risk for collateral damage.

SWERISK calculates risk distances according to several widespread simple empirical rules based on warhead weight (UN), explosive weight (NATO) or warhead diameter (NL). These rules do not give which risk levels corresponds to the calculated risk distances. As a complement SWERISK calculates probability of injury for different injury severities as function of location relative to the detonation point. These calculations are based on warhead construction, fragment ballistics and human vulnerability, and are computationally extensive. The injury probabilities are then combined and translated into three distinct levels of risk: acceptable, limited acceptable and unacceptable.

The program is intended to be used in field operations on an ordinary notebook. One consequence is that the computing resources are constrained, which impacts design philosophy, program structure, and the algorithms used. Measurements showed that the most resource consuming task was calculating fragment flight paths and associated parameters. Since one of the goals of SWERISK is to be a rapid and user-friendly tool, short calculation times is of paramount importance. In order to fulfil these goals, two different tracks were explored:

- *Take advantage of the rapid development in computer architecture and capability towards multi-core processors.*
- *Identify and develop fast and robust algorithms useful for modelling fragment ballistics.*

In this paper we present approximate algorithms for calculating the endpoint parameters associated with fragment flight paths, and discuss the delicate balance between desirable accuracy and required response time.

1.0 BACKGROUND

In explosive ordnance disposal (EOD) and demining operations, determining how large an area must be sealed off can be a delicate problem. There are several widespread simple empirical rules for determining a safety distance, based on warhead weight (UN), explosive weight (NATO) or diameter (NL). These rules do not indicate what injury severity corresponds to the calculated distances. Another weakness is that they do not indicate how the safety distance varies in different directions around the warhead, due to warhead or improvised explosive device (IED) construction details.

A safety distance is a binary measure, and sometimes a more nuanced measure of risk is needed. The affected area grows quadratic with the distance, and so does the number of personnel required for evacuation. Building barriers around the warhead can reduce the area, but the empirical rules does not account for barriers. In urban areas there may be adjacent buildings or infrastructure that is hard or expensive to evacuate. Knowing what levels of risk that is associated with a region would help making informed decisions, minimizing the risk to own troops and civilians, and for estimating the risk for collateral damage.

2.0 INTRODUCTION

SWERISK is a computer model for calculating the probability of a human being hit and injured by fragments from a detonating warhead. Development of SWERISK started in 2007 with the goal to create an easy to use computer program for the calculation of risk distances in EOD and demining operations. FOI got a commission from SWEDEC (Swedish EOD and Demining Centre) for this work. It was from the outset intended as a fast field instrument to support the crucial task of quickly determining how large an area must be sealed off, keeping the risks that own troops and civilians are exposed to on acceptable levels.

SWERISK calculates probability of injury for three different injury severities: lethal, serious and non-serious injury, as a function of target position relatively to the detonation point. These calculations are based on warhead construction, fragment ballistics and human vulnerability. For each injury severity there are two associated distinct risk limits:

- *acceptable*, meaning that probability of injury is not higher than what we are normally exposed to in everyday life
- *unacceptable*, meaning that probability of injury is so high that it is unacceptable to expose anyone for such risks in their everyday life.

The level of risk between those two limits is denoted *limited acceptable*, meaning that being exposed to this level of risk is acceptable under certain conditions [5]. It is regions with this level of risk that an operation leader maker can, or sometimes must, elaborate with.

The program is intended to be used in field operations on an ordinary notebook, but the computations, especially fragment ballistics, are quite extensive. As computing resources are constrained, this impacts design philosophy, program structure and algorithms used. Field usage also puts certain constraints on usability. The user interface must be clear and unambiguous, with a well-defined and intuitive workflow. Thus, the user interface contains only fields considered necessary for operation.

The intended usage scenario is where the user is skilled and experienced in demining operations, and has access to information about the object that is relevant for predicting how it will fragment. SWERISK is not supposed to be the only means for dimensioning the area to be sealed; there will be certain aspects of the situation that cannot be captured by SWERISK, such as protruding warhead parts, or other uncertainties.

3.0 PROGRAM PHILOSOPHY

A detonating warhead can injure a human being in many ways by blast, heat, pressure and fragments. Fragments have the largest range of them all, and thus define the risk area. Damage from fragments is the only weapon effect considered in SWERISK.

SWERISK is based on physical modelling of the chain of events from fragment generation to target impact and calculation of probability of injury, as illustrated in Figure 1. This is very similar to how many weapons effect models operate. As many of the events in the weapon effect process are of stochastic nature, the Monte Carlo technique is often used when calculating damage probabilities.

This approach is unfortunately not effective in risk evaluation when the computational power is restricted, and results are required within minutes. When calculating weapon effects, the probability of injury often is measured in tens of percents, and the number of Monte Carlo cycles to get a significant figure is counted in perhaps hundred thousands. Risk probabilities are often in the region of one per thousand or even one per million, with a corresponding very large increase in the number of Monte Carlo cycles. As a consequence of the time constrains, all computations in SWERISK are deterministic.

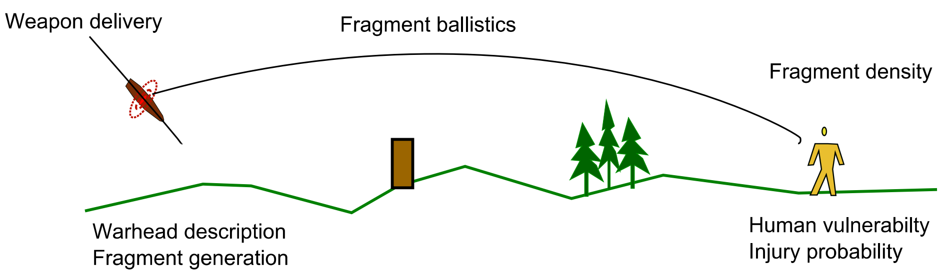

Figure 1. The chain of events modelled in SWERISK.

4.0 USER INTERFACE

The user interface in SWERISK (illustrated in Figure 2) is designed to coincide with the workflow of a demining operation. The interface is compartmentalized in tabs, where each tab corresponds to a distinct step in the demining process.

The starting point is to describe the warhead characteristics, by selecting a warhead from a set of predefined table of common warhead types, such as artillery shell, mortar grenade, general purpose bomb, and different kinds of IED. The warheads are defined in a text file, and each one is built up of sections that describe shell geometry, construction and initiation point. The user can stretch or compress the warhead both in length and diameter and also change the shell thickness, to improve similarity with the demining object. One can also choose a suitable explosive and specify fragmentation characteristics, e.g. brittle steel which will give a large proportion of small fragments, or ductile steel, which mainly will give fewer but heavier fragments.

The knowledge of the demining object can vary significantly from case to case. Sometimes there may be opportunities to take x-ray pictures, other times there may be only coarse measures on the outer geometry available. When warhead characteristics are defined, SWERISK can immediately present risk distances calculated derived from empirical rules, and visually relate them to each other. The presentation of these risk distances is located on a separate tab, to avoid feedback when defining the warhead.

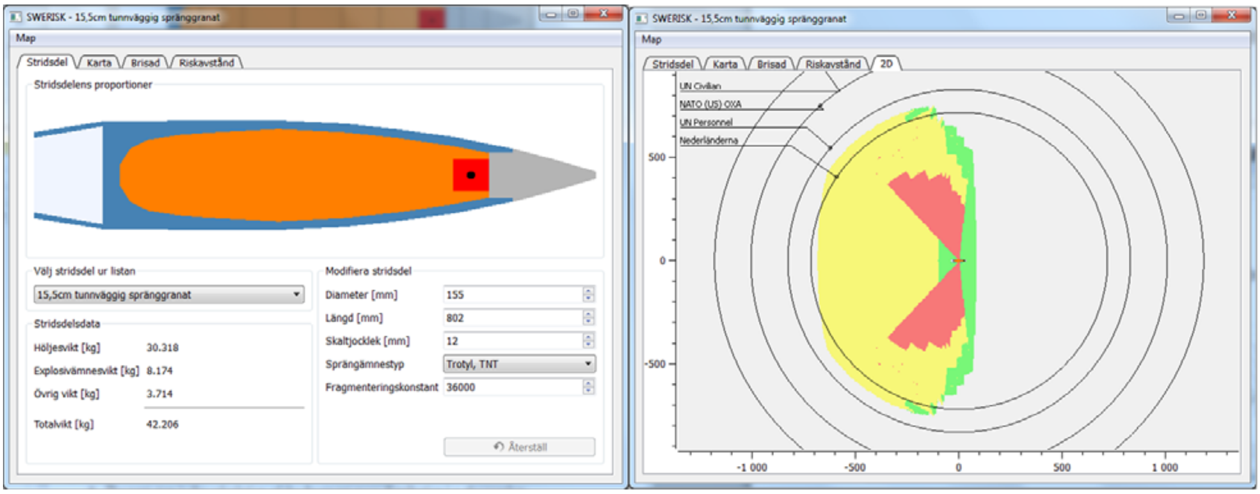

Figure 2. Warhead description and result presentation.

The result from SWERISK is presented as a map, with three distinct levels of risk. This is a simplistic presentation that hides many details and assumptions. The main reason for choosing such a simplified view over one that potentially would hide less detail is that we have found that an individual's interpretation of the simplistic view is more predictable, and thus less susceptible to variations.

Regions hit by fragments are coloured in green, yellow and red. Red implies that risks for any of the predefined types of injury are considered too high. Green indicated that the region is hit by fragments, but all levels of risks are acceptable. The yellow region is the one that operation leader can relate to, and elaborate with. If the circumstances make it impossible to evacuate and seal off the entire area, one might accept an elevated risk within some portions of the area. Another option is to add barriers, and rerun the simulation until the risk area matches what realistically can be evacuated and sealed.

There are a few problems in SWERISK that remains to be solved. The warhead is modelled as a tube bomb, which does not consider the flanges. In practice, the rear flange may be ejected more or less intact, as a very large and dangerous fragment. This is not shown in the result, as it is hard to determine the size of the affected sector. Another issue is how large the maximum fragment size should be, which in theory corresponds to the infinite tail of the fragment mass probability distribution. Still, with those weaknesses considered, we argue that the coloured map contributes significantly to an operation leader's ability to make informed decisions in EOD operations.

5.0 FRAGMENT GENERATION AND DENSITY

In order to calculate hit- and injury probabilities, deterministic measures are needed for how the warhead will fragment, and how those fragments hit the target, e.g. the fragment density (number of fragments/m^2) at impact point, the fragment mass, and impact velocity and angle. For fragment mass we use a discrete representation of a statistic distribution, prescribing the relation between the numbers of fragments in different mass ranges. We cut the distributions tail by discarding mass ranges containing fewer than 10^{-1} fragments.

The warhead is modelled as a rotational symmetric tube bomb, divided in a set of adjacent sections. The geometry of each section defines the explosive loading which is used to calculate a local fragmentation value which in turn is used to calculate the mass distribution, i.e. the number of fragments in different mass classes for a section. We use a formula for this developed at FOA in the sixties [1]. The ejection velocity and ejection angle at the border between the sections is calculated in accordance with Taylor's ejection formula[2]. The ejection velocity and angle is assumed to vary linearly within in the section between the borders.

To simplify calculation of the fragment density each warhead section is divided in radial sectors, as illustrated in Figure 3. The shell mass of a radial sector is easy to calculate, and in combination with the fragment distribution, we know the number of fragments and their masses in each radial sector. By computing trajectories from the radial sector's corner points, we can map that sector to a quadrilateral area on ground. By making the radial sectors angle and length small enough, we can assume constant fragment density (perpendicular to the trajectory at the impact point) within each quadrilateral.

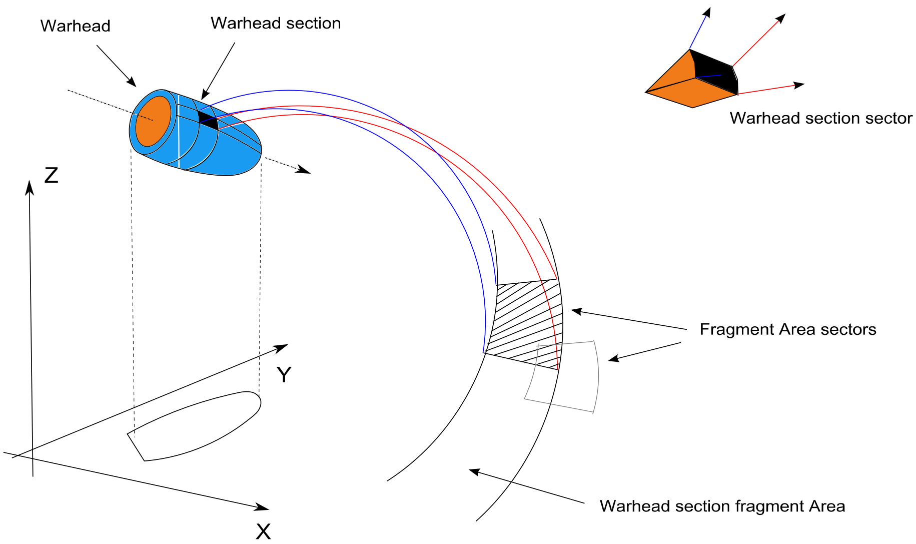

Figure 3. Calculation of fragment density, here illustrated for one radial sector, from a single warhead section, and one mass range.

One interesting characteristic with this approach is that it makes calculation of fragment density a highly parallelizable problem. For a warhead with m sections and n mass ranges, calculation of fragment density can be divided into $m \cdot n$ independent tasks. Thus, SWERISK can fully utilize multi-core CPUs, which reduces response time.

6.0 BALLISTICS

Like all flying objects fragments are influenced by two forces: aerodynamic drag and gravity. Gravity, can in the fragment case, be assumed be constant and only influenced by latitude on earth. The problem is the aerodynamic drag which is highly nonlinear and which has engaged great mathematicians and physicists from Galileo and onwards. The ballistic problem can be formulated in two nonlinear coupled differential equations which cannot be solved analytically.

A simple 2-DOF point mass model has been chosen to describe the fragment ballistics and the differential equations are solved numerically by the Runge Kutta method. The result is very accurate but also time consuming when roughly hundred thousand trajectories must be calculated in order to establish the injury probabilities in the risk area around the detonation point. In order to investigate possible solutions two questions was considered:

- Is the very high precision needed? The answer is no. The uncertainty in human vulnerability and fragment air drag coefficient is greater than the precision in trajectory calculation.

- Is the complete fragment trajectory needed? That depends. Usually it is not necessary. Impact data is sufficient in the form of impact point, velocity and angle to calculate injury probability. The exception is if premature impact is possible due to terrain topography, buildings and shieldings.

The simplest case is when the fragments are ejected in high ejection angles (>≈ 20º). The velocity is practically constant (Figure 4) and the impact angle (Figure 5) is close to 90º and can be quite easily approximated by an exponential function.

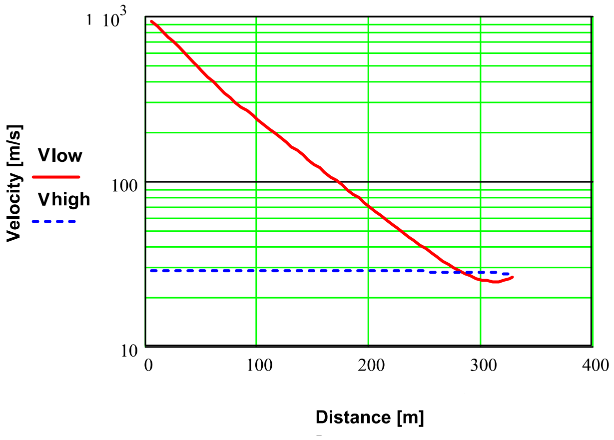

Figure 4. Velocity as a function of impact distance. The low trajectory is solid red and the high trajectory dashed blue.

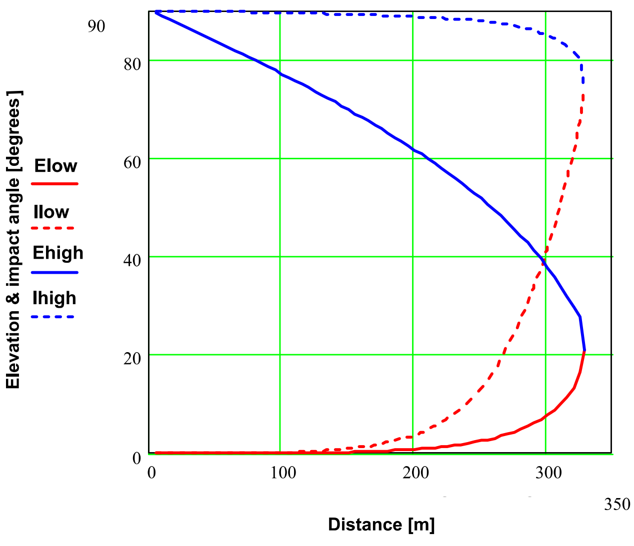

Figure 5. Elevation (solid line) and impact angle (dashed line) as function of distance. Low trajectories are red and high trajectories blue.

The curves in Figure 4 and Figure 5 are calculated using the Runge Kutta routines for a fragment with mass 10 grams and ejection velocity 1000 m/s.

The low trajectories are not as easily generalised, mainly due to the large variation in the aerodynamic drag coefficient as can be seen in Figure 6 below. SWERISK can handle three types of fragments: spheres, cubes and shell fragments. The drag coefficients for shell fragments are not very well known and the curve in the figure is an approximation and large variations can be expected in real life due to varying form and flight characteristics.

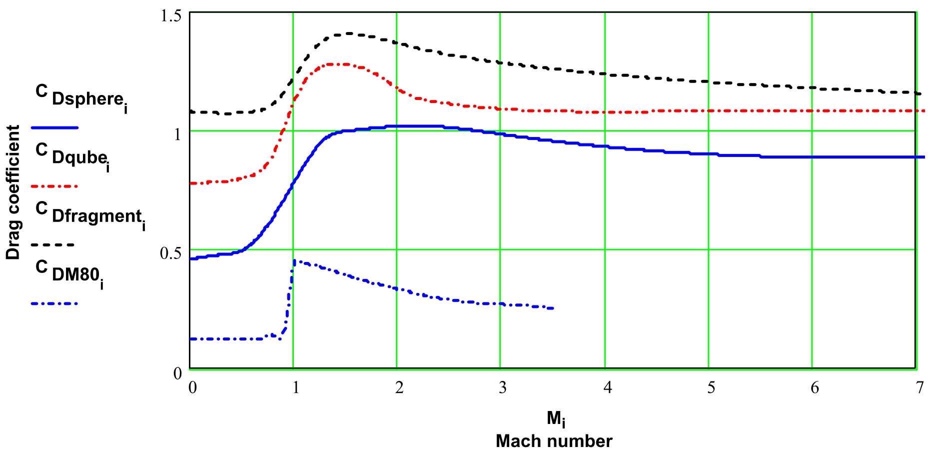

Figure 6. Aerodynamic drag coefficient for three different fragment types and M80 7.62 mm bullet.

A first step in the simplification process is to modify the calculation of the aerodynamic drag force *D*

$$D = ½ * Cd(Ma(h)) * \rho_{air}(h) * V^2 * A \qquad (1)$$

The aerodynamic drag coefficient *Cd* is a function of the Mach number *Ma* which in turn is a function of the height *h*. The air density ρ_{air} is also a function of height. *A* is the cross section area of the fragment.

For low trajectories the height variations are so small that the air density and Mach number dependence on height can be ignored and be calculated relative to air conditions at the detonation point.

A report ARL [4] investigates the possibility to analytically solve the ballistic equation. They have observed that *Cd* in the supersonic regime can be described, at least for projectiles, by the following equation:

$$Cd(Ma) = C / Ma^n \qquad (2)$$

The constant *C* and exponent *n* is determined by curve fitting to the actual Cd-function. The presented ballistic formulas are surprisingly simple. Unfortunately the supersonic region is often just a small part of the fragment trajectory.

7.0 VULNERABILITY AND INJURY CALCULATIONS

The target in SWERISK is a standing human being facing the detonation point. The “standard” person is 175cm tall with a frontal area of about 0.5 m^2. The body is structured in four regions with different probability of injury: head and neck, chest, abdomen and limbs. Three levels of injury severity are defined: *death*, *serious injury* and *non-serious injury*. Probability of death and serious injury are defined as functions of fragment kinetic energy. Probability of non-serious injury is considered to be equivalent to probability of skin penetration, which is a function of fragment kinetic energy density (J/m^2). Figure 7 exemplifies this type of function which is used in SWERISK.

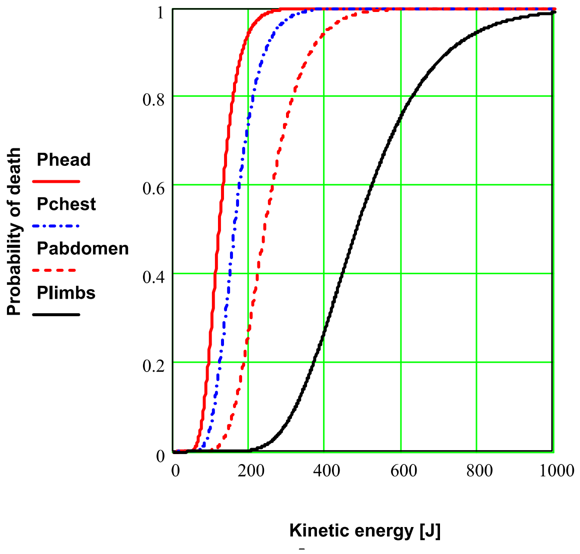

Figure 7. Probability of death as a function of fragment kinetic energy.

The deterministic calculation of injury probability for a given target position is given by the following equation:

$$P_{injury} = 1 - \prod (1 - Pih)^{N \bullet A} \quad (3)$$

Pih is the probability of injury if hit by one fragment and is described as a function of fragment kinetic energy for different body parts. *N* is the fragment density (number of fragments/m^2) at the target position for a fragment track which hits the human and *A* is the target area perpendicular to this fragment track. The product mark $\prod$ signifies the product for all different fragment sizes which are ejected from the warhead and hits the target. A weakness of equation 3 is that the probabilities *Pih* are assumed to be independent of each other which can lead to an underestimation of P_{injury}.

Probabilities of injury are calculated as a function of target position by sampling the area, and calculate injury probability for a large number of points, for each injury severity. The resulting surface is illustrated in Figure 8. These surfaces are then used for determining which level of risk that should be assigned for a given coordinate, by examining the probability at each point against the risk limits that are associated with the injury severities. If probability for any of the severity types is above unacceptable level, the coordinate is coloured as red, otherwise if probability is above acceptable level, the coordinate is coloured yellow. Coordinates that are hit by fragments, but with injury probability below acceptable level are coloured green.

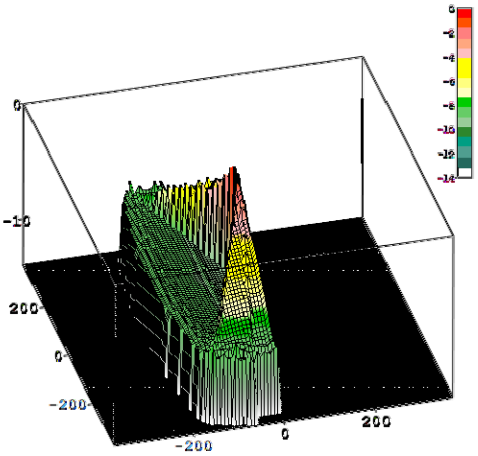

Figure 8. Resulting probability surface for one injury severity when all warhead sections and mass ranges are combined.

8.0 REFERENCES

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